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SINGLE STAGE, LOW NOISE, ADVANCED TECHNOLOGY FAN

VOLUME III ACOUSTIC DESIGN

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16. Abstract

The acoustic design for a half-scale fan vehicle, which would have application on an advanced transport aircraft, is described. The single stage advanced technology fan was designed to a pressure ratio of 1.8 at a tip speed of 503 m/sec (1650 ft/sec). The two basic approaches taken in the acoustic design were: 1) minimization of noise at the source, and 2) suppression of the generated noise in the inlet and bypass exhaust duct. Suppression of the generated noise is accomplished in the inlet through use of the "hybrid" concept (wall acoustic treatment plus airflow acceleration suppression) and in the exhaust duct with extensive acoustic treatment including a splitter. The goal of the design was attainment of twenty effective perceived noise decibels (20 EPNdB) below current Federal Air Regulation noise standards for a full-scale fan at the takeoff, cutback, and approach conditions. Predicted unsuppressed and suppressed fore and aft maximum perceived noise levels indicate that the cutback condition is the most critical with respect to the goal, which is probably unattainable for that condition. This is also true for aft radiated noise in the approach condition.

This report, entitled Volume III - Acoustic Design is one of three in a series of design reports for the advanced technology fan. Other reports in the series include: Volume I - Aerodynamic Design and Volume II - Structural Design.

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SECTION I

SUMMARY

A high speed, low noise, high bypass ratio, single-stage research fan with two booster stages and a variable-geometry inlet has been designed by the General Electric Company under the sponsorship of NASA (Contract No. NAS3-16813). This report, entitled Volume III - Acoustic Design, is one of three in a series of design reports for the advanced technology fan. It presents the acoustic design of this low radius-ratio fan and booster and the acoustic design of the inlet and bypass exit ducts suitable for an advanced transport aircraft engine. Other reports in this series include: Volume I - Aerodynamic Design and Volume II - Structural Design, which are References 1 and 2, respectively.

The fan and booster components are designed in a scale-model flow size convenient for testing with existing facility and vehicle hardware. The design corrected flow per unit annulus area at the fan face is 215 kg/sec m^2 (44.0 lbm/sec ft^2) with a hub-tip ratio of 0.38 at the leading edge of the fan rotor. This results in an inlet corrected airflow of 117.9 kg/sec (259.9 lbm/sec) for the selected rotor tip diameter of 90.37 cm (35.58 in).

The goal of the acoustic design was attainment of FAR 36-20 EPNdB for a full-scale fan at the takeoff, cutback, and approach conditions. The two basic approaches taken in the acoustic design were, 1) minimization of noise at the source and 2) suppression of the generated noise in the inlet and bypass exhaust duct.

Acoustic design considerations applied to minimize the generated fan noise consisted of the following:

1. Rotor noise alone

    Selection of a large number of blades
    Selection of a moderately high design speed
    Tip pressure ratio lower than average
    No midspan shroud
    Blade designed for swallowed shock at takeoff

2. Interaction Noise

    Bypass vane/blade ratio = 2.045
    Bypass rotor/stator spacing = 2.06 (tip rotor chord)
    Booster vane/blade ratio = 1.86
    Booster rotor/stator spacing = 0.90 (hub rotor chord)

The variable-geometry inlet is designed utilizing a combination of high throat Mach number and acoustic treatment in the inlet diffuser for noise suppression (hybrid inlet). A variable fan exhaust nozzle was assumed in conjunction with the variable inlet throat area to limit the required area change of the inlet throat at approach and hence limit the overall diffusion and inlet length.

The inlet acoustic treatment design is four segmented SDOF treatment tuned to various dominant frequencies and has an overall treated length, $[L/D]_{treat}$, of 0.85. The remainder of the suppression is accomplished by setting adjustable inlet panels to provide a high throat Mach number (M_{TH} = 0.79) at all three critical noise conditions. The exhaust duct provides extensive suppression through four segmented treatment panels plus a treated splitter for increased treated surface area and reduced effective duct height. The treated panels are tuned to the various dominant frequencies and provide large amounts of calculated suppression at all three critical noise conditions.

Comparison of the goal PNL values with the predicted unsuppressed and suppressed fore and aft max. angle values indicates that the cutback condition is the most critical with respect to noise for the single-stage, low noise, advanced technology fan. A summary comparison of the maximum angle PNL's required to meet the goal with the predicted fully suppressed values is provided in the following table:

FULL SCALE-SINGLE ENGINE

	Description of Condition		Design Goal PNL_{max}. Required To Meet EPNL Goal		Predicted Suppressed PNL_{max}.	
Power Setting	Altitude Meters (Ft)	Measuring Point	Forward PNdB	Aft PNdB	Forward PNdB	Aft PNdB
Takeoff	248 (800)	457 meters-sideline	79.9	79.5	77.0	76.1
Cutback	390 (1280)	3.5 nautical miles	78.0	77.8	77.7	79.8
Approach	113 (370)	1.0 nautical miles	85.7	85.5	82.8	86.4

It should be noted that the suppressed inlet values are based on full addition of estimated acoustic treatment and airflow acceleration suppression within the hybrid inlet. This assumption is known to be optimistic, as discussed in the text.

SECTION II

INTRODUCTION

Low noise and exhaust emissions and economical operation are the primary requirements for advanced transport aircraft. The successful development and acceptance of a subsonic, long-range transport for the next generation are greatly dependent upon technological improvements in the areas of fan aerodynamics and acoustic suppression. To help provide this fan technology, the General Electric Company was contracted to design a high speed, low noise, single stage research fan with two booster stages (hereafter referred to as an advanced technology fan), a variable inlet and an acoustically treated fan exit duct, all applicable for an advanced high bypass, low noise engine. To utilize existing hardware and facilities, the subject fan was designed to be half scale.

Under a separate and earlier contract with NASA (Contract NAS3-15544, References 3 and 4), parametric studies were performed to optimize the engine cycle characteristics for a typical advanced transport aircraft. Based on these studies, plus the current contract Statement of Work, an engine cycle was selected for an advanced transport designed to cruise between 0.85 and 0.90 Mach number. A fan pressure ratio of 1.8 to 1.9 and a bypass ratio of approximately 6:1 were determined to be desirable. Furthermore, it is desirable to raise the pressure ratio of the flow entering the core compressor to about 2.5 to 3.0 by the addition of booster stages. This then provides an overall cycle pressure ratio of 30:1 or greater and still uses only a single-stage turbine to drive the high pressure compressor. Fan tip speeds of 488 to 518 m/sec (1600 to 1700 ft/sec) are required to achieve the desired pressure ratio in a single, low radius-ratio stage with adequate stall margin. A high specific flow rate of 215 kg/sec m^2 (44.0 lbm/sec ft^2) was chosen to minimize fan diameter.

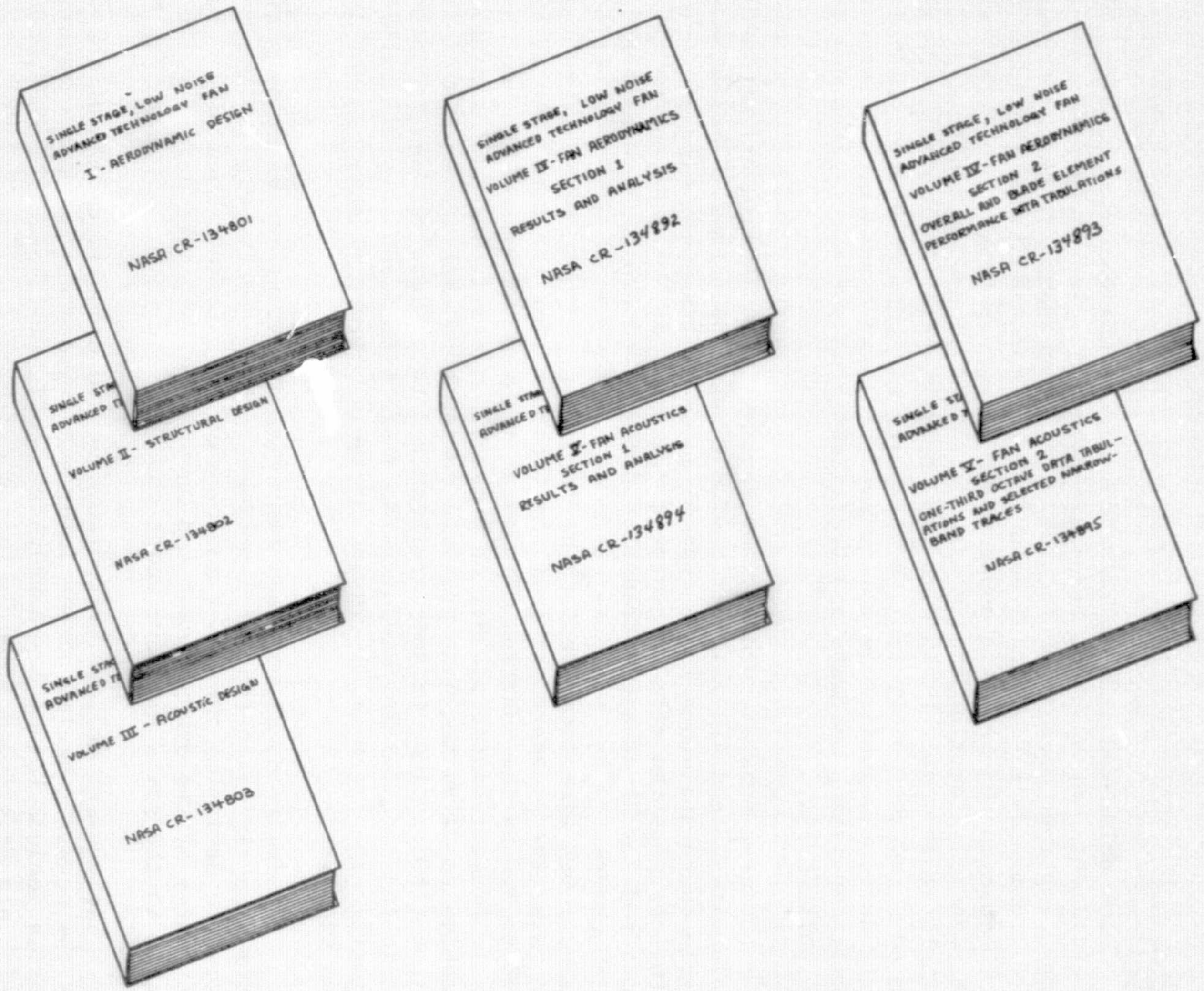
The design considerations employed in minimizing the noise generated by this high tip speed fan are described in this report. In addition, the acoustic design of the inlet and exhaust duct is described with corresponding estimates of the unsuppressed and suppressed perceived noise levels as compared to the goals set down under the Contract (FAR 36-20 EPNdB).

The present volume first discusses the acoustic design of the fan, followed by the acoustic design of the inlet and exhaust ducts. Other reports in this series include Volume I - Aerodynamic Design and Volume II - Structural Design, which are References 1 and 2, respectively.

A visual representation of the overall program and report organization is shown on the following page.

DESCRIPTION OF ADVANCED TECHNOLOGY FAN REPORTS

DESIGN REPORTS **ANALYSIS (FINAL) REPORTS** **DATA REPORTS**



SECTION III

FAN ACOUSTIC DESIGN

A. General Discussion

In general, the design of the advanced technology fan was directed primarily by engine cycle and aerodynamic performance considerations. The reasons being that a quiet fan with poor performance has no value, and because there are other means besides source noise reduction to limit fan noise propagation. To the extent practical, noise was a factor in the fan design, as described in Section IIIB, below.

The principle overall parameters which effect fan-stage noise generation are pressure ratio, tip speed, and radial work distribution. In stage aerodynamic design, these variables are, of course, interrelated; however, a degree of latitude does exist which can have a measurable effect on noise generation.

The combination of pressure ratio and tip speed has a significant effect on the characteristics of the rotor's wake and surrounding pressure field. Both of these phenomena will effect rotor-stator interaction noise. In addition, the rotor speed will have a direct bearing on the generation of multiple pure tones (MPT's). High speed operation also produces reduced loading at a given pressure ratio.

Finally, the radial work distribution coupled with the radial distribution of rotor-stator spacing will effect viscous wake interaction noise as well as MPT generation. Designing required high loading regions away from the tip and/or radial positions where rotor-stator spacing is relatively close will reduce noise generation.

B. Fan Acoustic Design Considerations

The fan components are designed in a scale-model flow size convenient for testing with existing facility and vehicle hardware. A summary of the most significant aero/acoustic design parameters is presented in Table I on the following page.

Table I. Fan Design Parameters.

Corrected Tip Speed	503 m/sec (1650 ft/sec)
Corrected Airflow	117.9 kg/sec (259.9 lbm/sec)
Tip Diameter	90.37 cm (35.58 in.)
Inlet Hub-Tip Radius Ratio	0.38
Bypass Rotor/Stator Spacing	2.06 rotor tip chords
Number of Rotor Blades	44
Number of Bypass Stator Blades (OGV's)	90

The fan-stage airflow and pressure ratio were selected based on parametric studies performed under an earlier program (References 3 and 4) and those on the current contract Statement of Work. Based on these two parameters, a design tip speed in the range of 472.4 to 533.4 m/sec (1550 to 1750 ft/sec) was considered. The high side of this range was rejected because of the likelihood of poor fan efficiency and strong MPT noise generation. The low side was rejected due to the lack of stall margin and because higher blade loading would result in strong blade passing frequency (BPF) tones. Thus, the midrange value of 503 m/sec (1650 ft/sec) was selected as the best design tip speed. The low radius ratio (0.38) was selected on the basis of minimizing the overall diameter. A lower than average tip pressure ratio was employed to help reduce the blade/tip loading and thus the stage-generated noise (see Reference 5). The design radial pressure distribution is shown in Figure 1. The selection of a large number of blades is consistent with the theoretical hypothesis that the attenuation of the MPT as they propagate forward in the inlet duct is greater for fans with a large number of blades (References 6 and 7).

A tip shroud design was chosen in preference to a midspan shroud for both aerodynamic and acoustic performance benefits. That is, acoustically, the additional periodic pressure-field disturbances created by a part-span shroud/fan rotor blade juncture would be expected to strengthen blade passing frequency tone generation. This effect was, in fact, measured experimentally on the original scale model Fan "C" blade at high speed during the Quiet Engine Program, where the identical blade was tested with and without a midspan shroud. The blades of the current fan were designed to have a "swallowed" shock at takeoff (92% $N/\sqrt{\theta}$). The intent, here, was to reduce the MPT noise level at this critical operating condition. This approach to reducing MPT's was successfully demonstrated in the Quiet Engine Fan "C" Scale Model Program (Contract NAS3-12430, Reference 8). An example of the results is presented in Figure 2, where the MOD II blade, designed to swallow the shock at about 100% $N/\sqrt{\theta}$), results are compared in the form of an SPL difference to MOD VIII blades, which was designed to swallow the shock at about 90% $N/\sqrt{\theta}$. The reduction in MPT level is obvious, although it was accompanied by an increase in blade passing frequency (BPF) and higher frequency noise.

It is well known that, at subsonic tip speeds, rotor/stator interaction noise is reduced as the vane/blade ratio is increased, and at all tip speeds when vane-blade spacing is increased. This is illustrated in Figure 3, which shows analytical study results from Reference 9 on blade passing frequency (BPF) noise. For this reason, the number of OGV's was set at 90 for a vane/blade ratio of 2.045 to help minimize fan source noise at the approach (subsonic tip speed) flight condition. The rotor/stator spacing, in true rotor tip chords, was set at 2.06. In the booster, the number of Stator 1 vanes was set at 82 for a vane/blade ratio of 1.86. The spacing between the fan rotor and booster Stator 1, in rotor hub chords was 0.90, which is untypically large for this parameter. The fan vehicle flowpath is shown in Figure 4. It should be noted that fabrication of the vehicle booster stages was never initiated.

In summary, the following acoustic design considerations were incorporated to minimize the advanced technology fan vehicle source noise -

1. Rotor noise alone

   Selection of a large number of blades
   Selection of a moderately high design speed
   Tip pressure ratio lower than average
   No midspan shroud
   Blade designed for swallowed shock at takeoff

2. Interaction Noise

   Bypass vane/blade ratio = 2.045
   Bypass rotor/stator spacing = 2.06 (tip rotor chords)
   Booster vane/blade ratio = 1.86
   Booster rotor/stator spacing = 0.90 (hub rotor chords)

SECTION IV

INLET ACOUSTIC DESIGN

A. Background

An extensive study of aero-acoustic inlet designs for an advanced aircraft/engine system, designed to cruise at $M_O = 0.90$, was conducted under an earlier contract (NAS3-15544) and reported in References 10 and 11. From an acoustics standpoint, three approaches were taken for suppression of the generated noise in the forward quadrant -

1. High throat Mach numbers; acceleration
2. Acoustic treatment suppression
3. A combination of 1. and 2.

Various schemes for achieving acceleration and/or treatment suppression were considered. Variable-geometry schemes were compared against a fixed-geometry inlet with multiple treated splitters in terms of suppression, performance, and mechanical integrity/reliability. The significant results and conclusions reached are summarized below:

a) The best inlet configuration relies on a combination of wall treatment and high inlet throat Mach number ($M_{TH} \leq 0.8$), i.e., a hybrid inlet.

b) The most attractive variable-geometry concept evaluated was a fixed external cowl with a variable internal surface.

c) A variable exhaust nozzle may be used to increase the throat Mach number while maintaining constant thrust. If a variable nozzle is unavailable, the geometry variation required in the inlet is more extensive.

d) The maximum noise reduction potential of variable-geometry inlets is limited by the maximum throat Mach number judged to be practical and realistic. This value would probably have to be established experimentally for a specific inlet geometry considering the range of operating conditions to be encountered.

e) The mission performance penalty for the hybrid inlet configuration is about 30% less than the TOGW penalty for a fixed-geometry inlet with multiple splitters (acoustic baseline inlet) that meets the noise objective. This corresponds to about 2% lower TOGW, 1.8% lower DOC and 1.2% higher ROI relative to the fixed-geometry acoustic baseline inlet (See Reference 10).

The last item expresses the merits of the hybrid variable-geometry inlet, which ultimately must be balanced against the increased complexity and risk that are introduced with any variable-geometry element.

B. Inlet Acoustic Design

A sketch of the selected hybrid inlet design is presented in Figure 5. Details of the aerodynamic design and performance predictions are contained in Reference 1 as noted earlier. The variable panels provide the capability of selecting the desired throat Mach number at takeoff, cutback, and approach (M_{TH} = 0.79) for acoustic suppression and the best performance geometry for the cruise and maximum climb conditions (M_{TH} = 0.695 and 0.775 respectively; based on inlet throat area and cycle airflow for these conditions). A more detailed drawing of the inlet model is provided in Figure 6. The throat area for takeoff and cutback are the same. The design throat Mach number (0.79) is maintained by a variation in nozzle area between the two associated tip speeds. That is, cutback has a lower fan tip speed, but a more open nozzle.

The acoustic design of the inlet can most simply be described by the stepwise procedure below (part of which applies to the exhaust duct design as well):

1. Estimate the unsuppressed SPL spectra characteristics and PNL directivity patterns for the three critical noise conditions, i.e., takeoff, cutback and approach.

2. Extrapolate the results of (1) to full scale (25,000 lb thrust/engine) flight conditions to obtain the unsuppressed flight spectra and PNL directivity.

3. Determine the PNL directivity pattern required to meet the FAR 36-20 EPNdB goal at the three critical conditions.

4. Establish an overall inlet treatment length, by employing both acoustic and aerodynamic performance criteria.

5. Based on the PNL suppression required, determined by the difference between (2) and (3), PNL directivity results, determine a balanced treatment design using segmented acoustic treatment as required, and limited to the overall length determined in (4).

6. Estimate the treatment suppressed flight spectra and PNL directivity for the three conditions based on (2) and (5).

7. Based on the difference between the treated PNL and required PNL (6. versus 3.), determine the additional acceleration suppression required to meet the goal, and set the design throat Mach number requirement accordingly. More specifically, using historical data on inlet airflow acceleration suppression, determine what throat Mach number is required to exceed slightly the goal suppressions when added to the estimated treatment suppressions. The additional

PNdB being to account for the fact that acoustic treatment and acceleration suppression are generally not additive, as determined by past experience. In addition, a limiting throat Mach number of 0.79 was set for inlet aerodynamic performance and airflow control system tolerance reasons.

The estimation of unsuppressed SPL spectra and PNL directivity patterns relied heavily on Quiet Engine Program (NASA Contract NAS3-12430) Engine "C" results (Reference 12). In scale-model size, Fan "C" and the advanced technology fan are compared in Table II below:

Table II. Comparison of Quiet Engine "C" Fan Design Characteristics with the Advanced Technology Fan Characteristics.

Characteristic	Fan "C"	Advanced Technology Fan
• Design tip speed m/sec, (ft/sec)	472 (1550)	503 (1650)
• Design pressure ratio	1.60	1.80
• Diameter cm, (in.)	90.37 (35.38)	90.37 (35.38)
• Number of blades	26	44
• Vane/blade ratio	2.31	2.05
• Vane/blade spacing	2.00	2.06

The General Electric measured Engine "C" noise characteristics were corrected in three ways to obtain correctly adjusted fan vehicle unsuppressed noise estimates. First, a correction was applied for a frequency shift due to blade number differences. Second, a correction to remove jet noise was applied to isolate the fan vehicle noise. Finally, Engine "C" SPL's were plotted versus fan relative tip Mach number for the entire range of third-octave band frequencies and inlet angles. By extrapolation and interpolation of these plotted data, it was possible to estimate unsuppressed SPL spectra of the advanced technology fan at the correct relative tip Mach number for each design condition, i.e. takeoff, cutback, and approach.

The predicted scale-model noise characteristics were extrapolated to full scale (25000 lb thrust/engine) flight conditions. These three critical conditions are described in Table III on the following page.

Table III. Predicted Noise Characteristics Extrapolated To A Full-Scale E gine.

Condition	% Design Fan Speed	Tip Speed m/sec(ft/sec)	Max. PNL Angle	Altitude Meters (Feet)	Acous. Rng. Meters (Feet)	Measuring Point
Takeoff	92%	462 (1517)	70°	248 (800)	551 (1809)	457 meters (1500) sideline
Cutback*	85%	428 (1405)	50°	390 (1280)	492 (1617)	3.5 nautical miles
Approach*	58%	294 (957)	50°	113 (370)	147 (483)	1.0 nautical miles
* A variable fan nozzle is implied by these conditions						

The resulting flight SPL spectra at the maximum forward angle are presented in Figures 7 through 9. Unsuppressed PN', directivities for both front and rear fan noise are shown in Figures 10 through 12. Also shown in these plots are the required PNL directivity patterns required to meet the FAR 36-20 EPNdB goals.

These required PNL's were determined using the criteria that the most optimum system has balanced PNL fore and aft, as indicated by the dashed line indicating equalizing suppression, and by assuming that the tone correction to EPNL would be eliminated with the treatment design suppression. The dashed line directivities were used to determine the corresponding EPNdB level at each of the three critical flight conditions. Then the suppression required, in addition to that needed to balance fore and aft directivities, was a fixed value on PNL over all the angles. A summary of the full-scale inlet suppression requirements is listed in Table IV below.

Table IV. Full-Scale Inlet Suppression Requirements.

Condition	EPNL Goal	Unsup. EPNL	ΔEPNdB	Front PNL_{max}. (Unsup	PNL_{max}. (Sup)	Required ΔPNdB
Takeoff	81.2	101.2	20.0	99.5	79.9	19.6
Cutback	78.2	103.8	25.6	104.1	78.0	26.1
Approach	81.2	99.1	17.9	102.2	85.7	16.5

It is seen that the cutback condition is by far the most critical with respect to meeting the goal. For information, the unsuppressed PNL levels on a 100 ft arc are presented for scale model size at the three flight conditions in Figure 13. These predictions represent the audible levels expected during the test of the fan vehicle.

Since acceleration of the flow was being employed to obtain additional inlet noise suppression, it was considered unnecessary to penalize the inlet length for purposes of additional wall treatment. Thus, the inlet length was set by aerodynamic performance design criteria, with the critical condition being approach (maximum diffusion angle condition). Treatment was then applied in the inlet over the length where the local Mach number was ≤ 0.70, since treatment is considered ineffective at Mach numbers greater than 0.70. This provided an overall effective treated length, $[L/D]_{treat}$, of 0.85. The resultant overall length of the hybrid inlet, from the fan face to the leading edge of the bellmouth lip, was 1.5 fan diameters.

A sketch of the optimized acoustic liner design for the scale-model, variable-geometry inlet is shown in Figure 14. As indicated, the treatment is of the SDOF type and is characterized by four different resonator cavity depths (4 segmented treatment). The lengths and tuning frequencies for each liner segment are listed in Table V below:

Table V. Inlet Acoustic Liner Lengths and Tuning Frequencies.

Liner	Length		Tuning Freq - Hz	
	cm	in.	Full Scale	Scale Model
Liner A	14.95	5.88	1000	2000
Liner B	35.20	13.82	2000	4000
Liner C	15.02	5.92	2500	5000
Liner D	10.17	4.00	4000	8000

The liner design can best be described by the following step wise procedure:

1. Selection of the liner tuning frequencies

2. Selection of faceplate thickness and porosity

3. Calculation of the cavity depth based on a reactance ratio of about - 1.0.

4. Selection of the length of each segment

The tuning frequencies were determined by inspecting the unsuppressed SPL spectra for the three critical flight conditions considered simultaneously, and by the knowledge that the cutback condition required the most suppression to meet the goal. These spectra are presented as the solid lines in Figures 15 through 17, with the liner tuning frequencies indicated. Thus, the selection was based on achieving the maximum treatment suppression at the cutback condition, but with coverage for the important takeoff and approach frequencies. No treatment was tuned to frequencies below 1000 Hz (full-scale frequency), since experience has shown that considerable lower frequency suppression is often obtained without having a liner segment tuned to the lower bands.

Extensive data on inlet multisegmented treatment suppression has been obtained at General Electric's Corporate Research Center Anechoic Chamber facility using NASA's high speed, Rotor 11, fan. About fifteen different combinations of segmented treatment were tested. These tests and others, as well as theoretical considerations, indicated that faceplate porosities on the order of 6% open area should provide good treatment suppression results and that faceplates should be as thin as practical. This experience was used to set the plate open area and thickness at 6.0% and 0.036 cm (0.014 in.) respectively. Having selected the tuning frequencies, the cavity depth was then determined by setting the reactance, which is a function of frequency, duct Mach number, faceplate porosity and thickness, at a value of -1.0. Experimental results have shown that this value of reactance provides maximum suppression at the selected frequency. An example of this experience is provided in Figure 18 which shows some of the Rotor 11 test results mentioned above. Part (A) of the figure shows the power level suppression for two different liners tested. Part (B) provides the results of the reactance ratio calculations for each liner, based on Groeneweg's model for acoustic liners (Reference 13). It is seen that the maximum suppression frequencies correspond to those at which the reactance is nearly -1.0. Similar results have been obtained in other tests. The calculated reactance for the four liners is provided in Figure 19. Note that each liner has a reactance of -1.0 at its respective tuning frequency. More detailed tuning studies, in the absence of detailed fan source noise information, were not attempted.

Liners (B) and (C) were aimed at the high frequency cutback condition noise and accounted for about two-thirds of the total treated length. As noted above, this discrimination was made because the predicted unsuppressed spectra indicated this flight condition to be the most critical with respect to meeting the goal noise level. Liners (A) and (D) were designed for coverage of the lower and highest frequency suppression, respectively, to help obtain adequate bandwidth suppression for all three conditions. Data from the Rotor 11 segmented treatment tests mentioned above were used extensively in estimating the treatment suppressions for the advanced technology fan inlet. SPL suppression on configurations similar to the selected treatment design were adjusted for length differences, using the treated length to fan diameter ratios, and applied to the unsuppressed spectra as shown in Figures 15 through 17. Associated ΔPNdB and ΔPNLT suppressions were calculated for the flight spectra, including the Doppler effect, and are listed in Table VI.

Table VI. Calculated Inlet Flight Spectra Suppressions.

Inlet Configuration	Takeoff PNdB	$\theta_m=70°$ PNLT	Cutback PNdB	$\theta_m=50°$ PNLT	Approach PNdB	$\theta_m=50°$ PNLT
Untreated	99.5	104.1	104.1	105.6	102.2	104.3
Treated	86.7	91.1	87.4	88.9	92.5	95.9
ΔPNdB	12.8	-	16.7	-	9.7	-
ΔPNLT	-	13.0	-	16.7	-	8.4

In determining the throat Mach number required in the inlet for the additional suppression to meet the goal, the goal PNL values at maximum forward angle were compared against the treated values as indicated in Table VII below:

Table VII. Acoustic Suppression Required from Throat Acceleration Effect.

Condition	Goal PNL Req'd	Treated PNL	Acceleration ΔPNL Req'd
Takeoff	79.9	86.7	6.8
Cutback	78.0	87.4	9.4
Approach	85.7	92.5	6.8

Cutback was therefore still the critical condition in terms of meeting the goals. It is known that treatment suppression and acceleration suppression are not additive in hybrid inlets, because the acceleration appears to have an adverse effect on treatment effectiveness. It was thus decided to design the adjustable panels to provide an average throat Mach number at all three conditions of 0.79, which was considered the near maximum with regard to maintaining acceptable levels of inlet pressure recovery and controlling inlet airflow.

Based on available data, shown in Figure 20, this should result in acceleration suppressions $\geq$ 9.7 ΔPNdB. Since the treatment and acceleration suppressions are not additive and are configuration dependent, there is no way of predicting with a high degree of certainty the total suppressed inlet noise levels. However, if for purposes of comparison with the goal values, the two suppressions are added, and then the total subtracted from the predicted unsuppressed maximum PNL values, the following results (Table VIII).

Table VIII. Comparison of Inlet Suppression Estimates To Design Goal Requirements.

Condition	Goal $PNL_{max.}$ Required	Estimated Overall Suppressed $PNL_{max.}$
Takeoff	79.9	77.0
Cutback	78.0	77.7
Approach	85.7	82.8

Although the estimated suppressed levels are known to be optimistic, some possibility of meeting the goals is indicated.

SECTION V

EXHAUST DUCT ACOUSTIC DESIGN

The stepwise procedure for arriving at the exhaust duct suppression design was much as described for the inlet in Section IVB, except that all of the suppression was to be obtained with acoustic treatment. An additional correction was applied to the Engine "C" data to remove the MPT content from the aft-quadrant noise when arriving at the predicted unsuppressed spectra at maximum aft angle. This was done by applying a straight-line variation of SPL versus frequency on the semilog third-octave band spectra from between the level at 160 Hz to the level one-third octave band below the blade passing frequency. This procedure was employed after examination of aft-quadrant MPT content in the basic Engine "C" third-octave data. These MPT's propogated from the inlet, and therefore had to be eliminated from the estimates of isolated fan exhaust duct unsuppressed noise spectra.

The philosophy of the suppression design, shown in Figure 21, was to utilize as much of the duct surface area as possible and an acoustic splitter to reduce the duct height parameter (H/λ) and add treated area. The aerodynamic design of the exhaust duct is covered in Reference 1 as noted earlier. The inner duct wall treatment is terminated sooner than the outer to allow for development of a core-stream mixer nozzle, determined beneficial in earlier installed performance cycle selection studies. The four-segment acoustic treatment liners are tuned to the various dominant frequencies as indicated below:

Table IX. Fan Exhaust Duct Acoustic Liner Lengths and Tuning Frequencies.

Wall Liner	Approx. Length cm	Approx. Length in.	Tuning Frequency, Hz S/M	Tuning Frequency, Hz F/S
A&B	41.1	16.2	8000	4000
C	61.8	24.3	5000	2500
D	25.6	10.1	1600	800
Duct Splitter				
B	17.2	6.8	8000	4000
C	50.4	19.8	5000	2500

The unsuppressed spectra at the maximum aft angle are shown compared to the suppressed spectra in Figures 22 through 24. Also shown in Figure 22, as an example, is the MPT content which was present in the Engine "C" data at the 120° inlet angle, and which was corrected out of the spectra as explained earlier. These spectra are for the full-scale (S/M frequencies superimposed on the abscissa) engine at the critical flyover points. The treatment was designed for the lowest-order, least-attenuated mode with a specific reactance ratio at the tuning frequency, f_o, of

$$\frac{X}{\rho c} = -0.77 \; H/\lambda_p \qquad \text{(Reference 14)}$$

where

H = height of the duct, i.e., the distance between the two opposite walls lined with the same optimized liners.

λ_p = wavelength (includes flow effects) = $c(1 \pm M)/f_o$

c = velocity of sound

M = duct Mach number + exhaust condition
- inlet condition

The treatment was designed for the lowest-order (plane wave) mode, since experience has shown that significant suppression of the higher order spinning and radial modes will occur in the exhaust duct without having the treatment tuned for these modes. This is different from the inlet, which, regardless of the tuning, never provides significant lower-mode attenuation, primarily because of the high value of H/λ_p involved. At the tuning frequency, the peak transmission loss per unit L/H, where L is the effective liner length, was determined according to

$$TL_{opt} = 7/(H/\lambda_p) \text{ in dB}$$

For each liner segment, the values of TL_{opt} were combined with appropriate bandwidth curves which were used to determine the transmission loss at the other midband frequencies.

The total suppression, then, is just the linear sum of the frequency's transmission losses for each segment. The specific reactance for each liner segment as a function of frequency is shown in Figure 25. The full-scale flight PNL, determined from resulting suppressed spectra, is shown compared to the goal values in Table X.

Table X. Comparison of Fan Exhaust Duct Suppression Estimates To Design Goal Requirements.

Condition	Goal PNL Required	Estimated Suppressed Maximum PNL
Takeoff	79.5	76.1
Cutback	77.8	79.8
Approach	85.5	86.4

Thus, it is seen that the approach and cutback conditions are the most challenging cases. However, it does appear that there is a reasonable chance of meeting or nearly meeting the goals, particularly at the takeoff condition. This is true for the front quadrant as well as the back. A cross-section drawing of the exhaust duct model is provided in Figure 26.

SECTION VI

RÉSUMÉ

The acoustic design for a half-scale fan vehicle, which would have application on an advanced transport aircraft, is described. The single-stage, low noise, advanced technology fan was designed to a pressure ratio of 1.8 at a tip speed of 503 m/sec (1650 ft/sec). The two basic approaches taken in the acoustic design were: 1) minimization of noise at the source, and 2) suppression of the generated noise in the inlet and bypass exhaust duct. Suppression of the generated noise is accomplished in the inlet through use of the "hybrid" concept (wall acoustic treatment plus airflow-acceleration suppression) and in the exhaust duct with extensive acoustic treatment, including a splitter.

The goal of the acoustic design was attainment of FAR36 (1969) minus 20 EPNdB for the full-scale fan at the takeoff, cutback, and approach conditions. Estimates of the fully suppressed configuration noise indicate the cutback condition to be the most critical with respect to meeting the goal, particularly as regards aft-quadrant noise. Specifically, the estimates show that the required peak aft-angle PNL to meet the goal will be missed by about 2 PNdB.

APPENDIX A

LIST OF SYMBOLS AND NOMENCLATURE

Symbol	Description	Units
BPF	Blade passing frequency	Hz
c	Speed of Sound	m/sec
d	Diameter (of acoustic-treatment faceplate hole)	cm
DOC	Direct operating costs	
EPNL	Effective perceived noise level (tone + duration corrected PNL)	EPNdB
EPNdB	Effective perceived noise decidels	
FAR	Federal air regulation	
F/S	Full scale	
H	Duct height	cm
L	Length (of acoustic-treatment linear)	cm
$[L/D]_{inlet}$	Inlet length to fan diameter ratio	
$[L/D]_{treat}$	Acoustic-treatment length to fan diameter ratio	
M	Mach number (average duct)	
M_o	Freestream mach number	
MPT	Multiple pure tone	
M_{TH}	Average inlet throat mach number	
M_{wall}	Mach number along inlet duct wall	
N	Fan speed	rpm
OGV	Outlet guide vanes	
PNL	Perceived noise level	PNdB
$PNL_{max.}$	Maximum perceived noise level	PNdB
PNLT	Tone-corrected perceived noise level	PNdB
PWL	Sound power level	dB
QEP	Quiet engine program	
R1,R2,R3	Designation of rotor stages 1, 2 and 3 respectively	
RE	Referenced to	
Rng	Range	
ROI	Return on investment	
S	Acoustic-treatment cavity depth	cm
S1,S2,S3	Designation of booster stators 1, 2 and 3 respectively	
SDOF	Single degree of freedom	
S/M	Scale model	
SPL	Sound pressure level	dB
Sup	Suppressed	
T	Temperature	°K
t	Thickness (of acoustic-treatment faceplate)	cm
TL_{opt}	Optimum transmission loss	dB
TOGW	Takeoff gross weight	
Unsup	Unsuppressed	
$X/\rho c$	Specific reactance ratio of acoustic treatment	
Z	Axial distance (relative to fan rotor leading edge)	cm
Δ	Change in	

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Symbol	Description	Units
θ	Temperature correction (T/518.67)	
λ_p	Length of plane acoustic wave	cm
ρ	Density	kg/m^3
$\sphericalangle m$	Maximum noise angle	degrees

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ILLUSTRATIONS

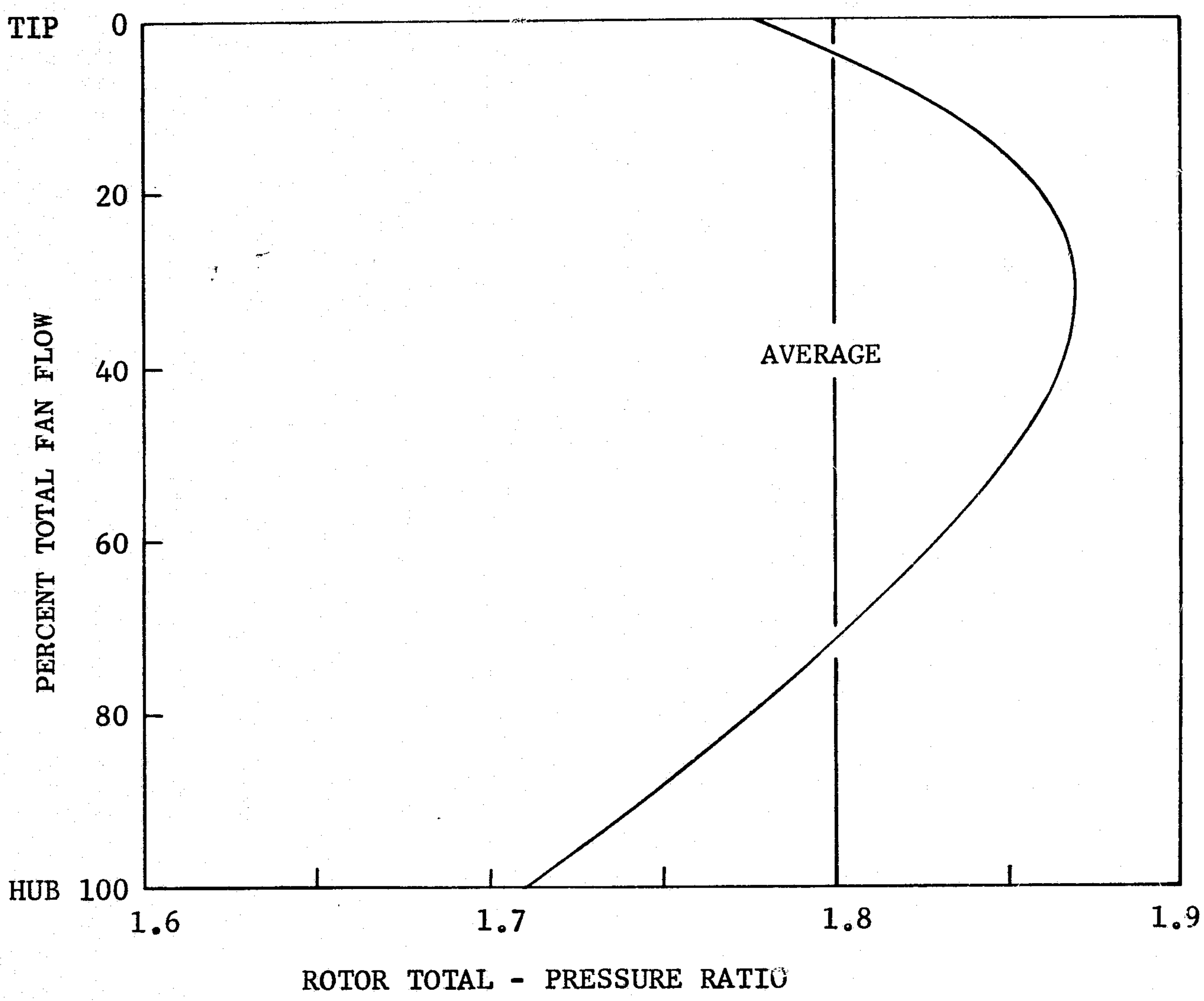


Figure 1. Advanced Technology Fan Design Pressure Ratio Distribution.

QEP FAN C SCALE MODEL - SCALED

61 METER (200') SIDELINE Δ SPL vs. FREQUENCY

- 70 DEGREES - TAKE-OFF
- UNTREATED

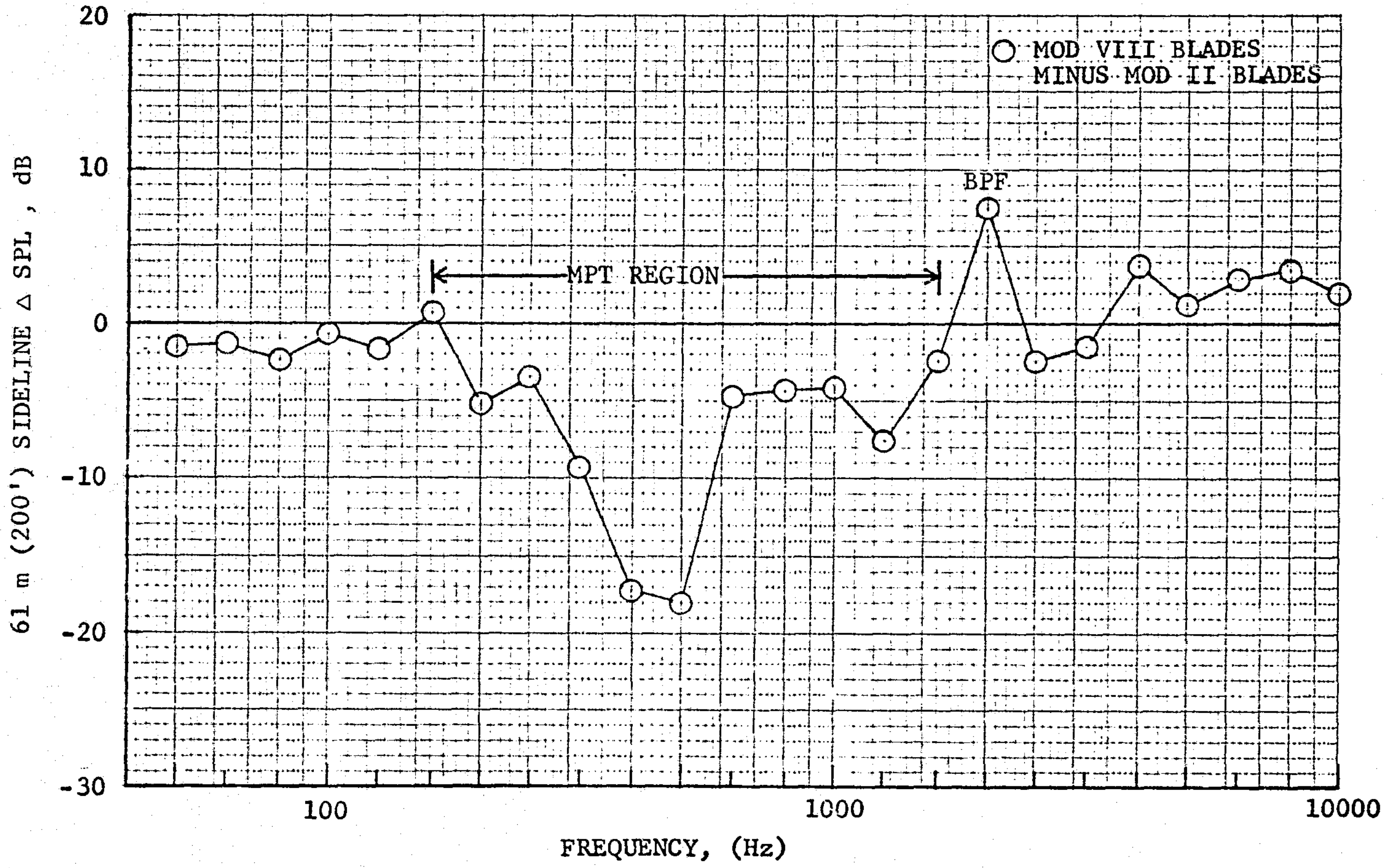
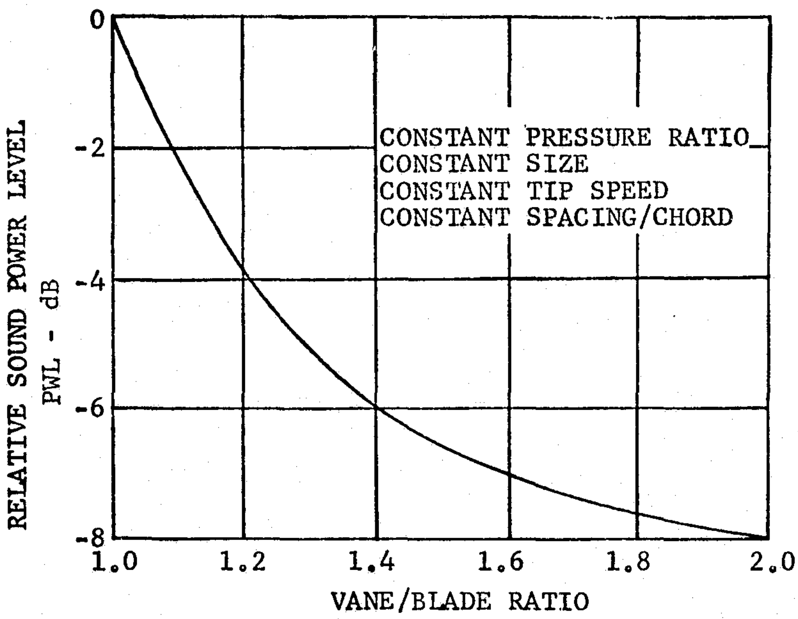
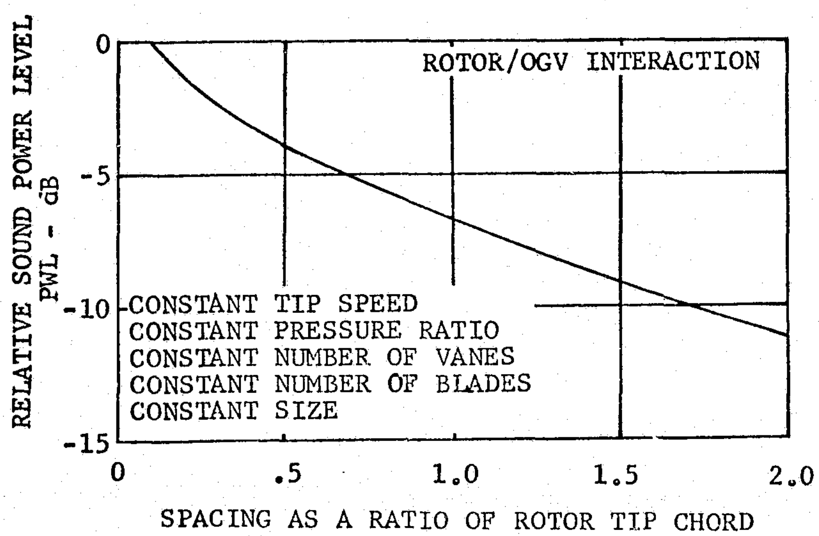


Figure 2. Effect of Shock Starting Speed Change on MPT Noise Generation.

NOTE: TAKEN FROM REFERENCE 9



a)EFFECT OF VANE-BLADE RATIO ON INTERACTION NOISE GENERATED AT THE BLADE PASSING FREQUENCY



b)EFFECT OF VANE-BLADE SPACING ON INTERACTION NOISE GENERATED AT THE BLADE PASSING FREQUENCY

Figure 3. Effect of Vane-Blade Ratio and Spacing on BPF Noise.

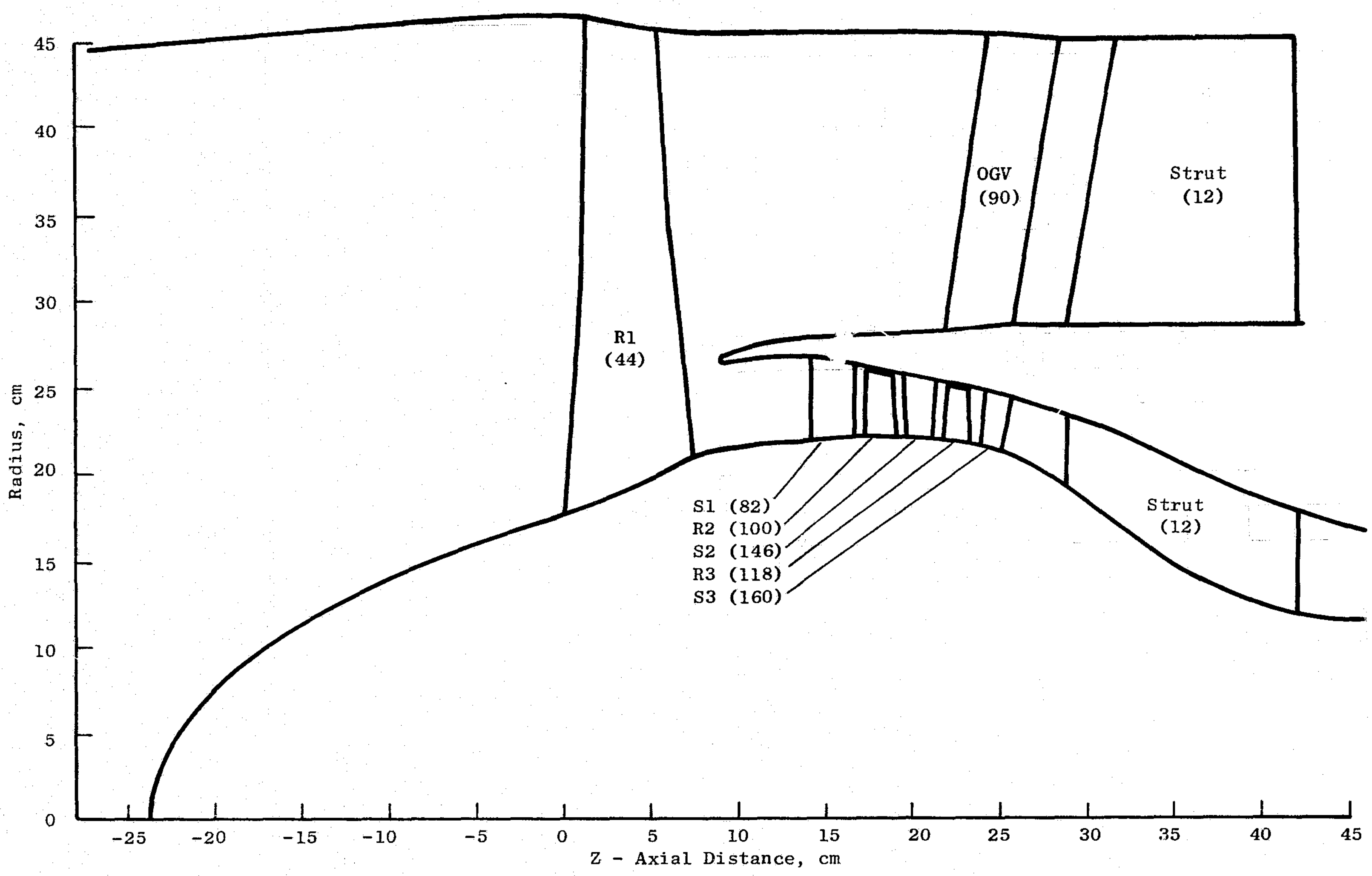
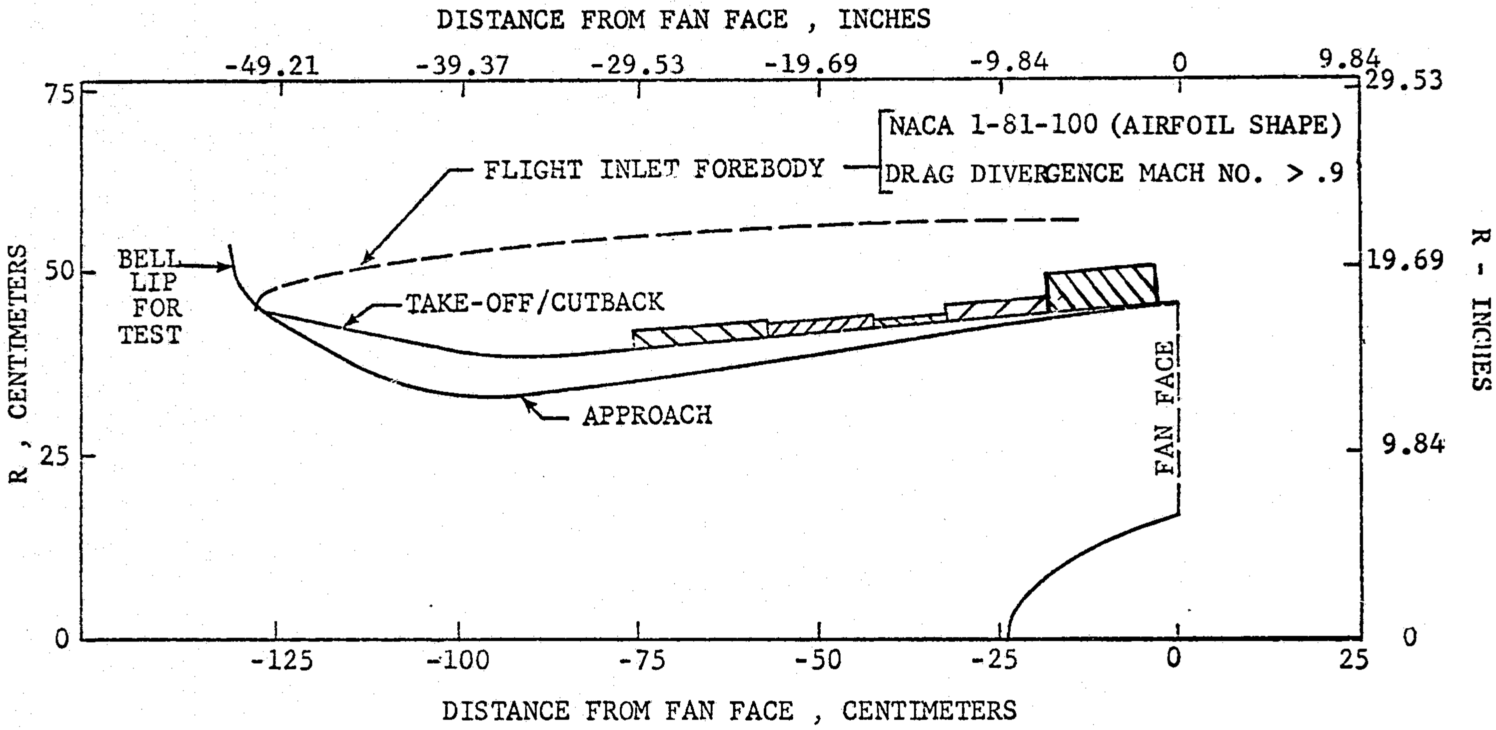


Figure 4. Fan and Booster Flowpath.



- Translating Panels and Variable Nozzle to Provide M_{TH} = 0.79 at all 3 Conditions
- 5 Sections of Treatment Tuned to Dominant Frequencies
- $[L/D]_{Inlet}$ = 1.5 (with Bell Lip), $[L/D]_{Treat}$ = 0.85
- Treatment Location where $M_{Wall} \leq 0.70$

Figure 5. Hybrid Inlet Design.

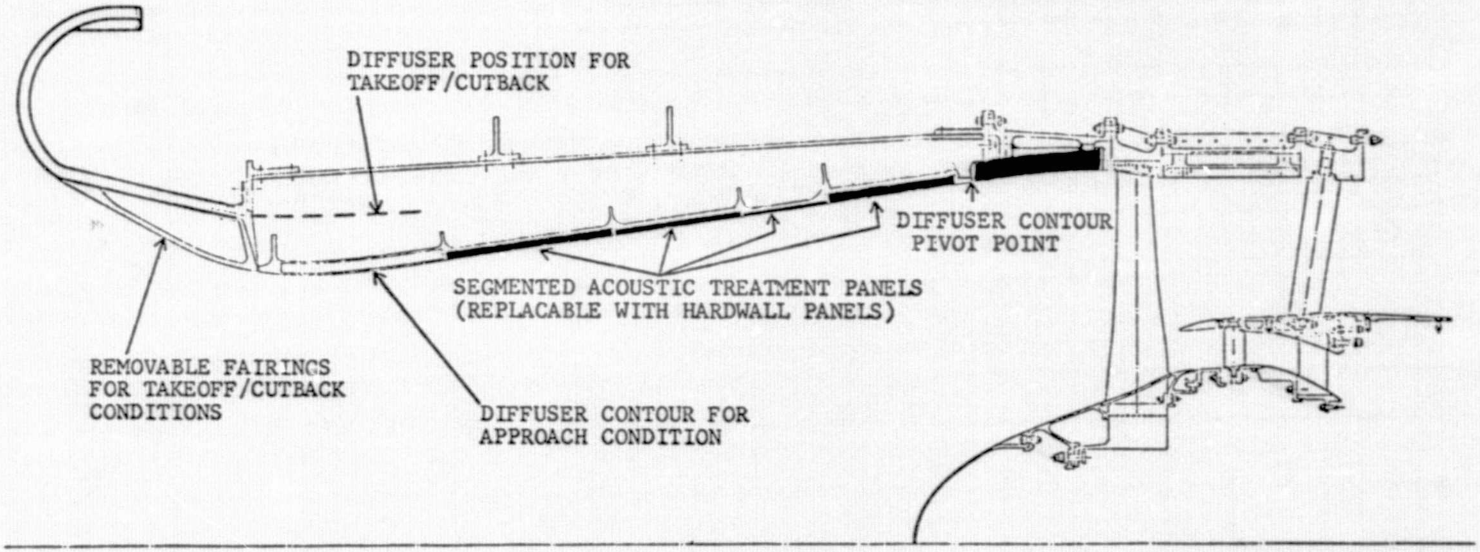


Figure 6. Cross Section of Fan Hybrid Inlet Suppressor Model.

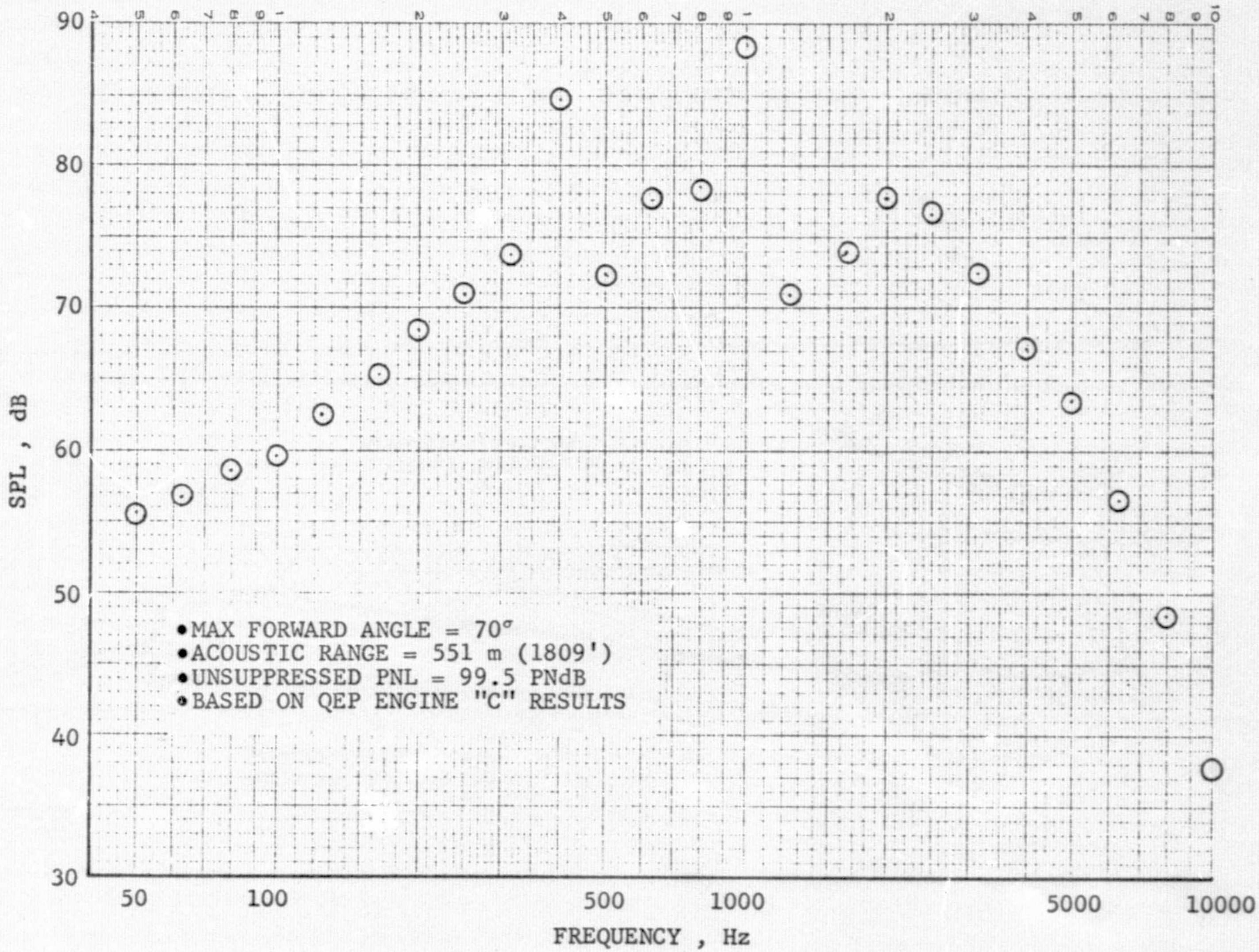


Figure 7. Estimated Full-Scale Unsuppressed Flight Spectra - Takeoff.

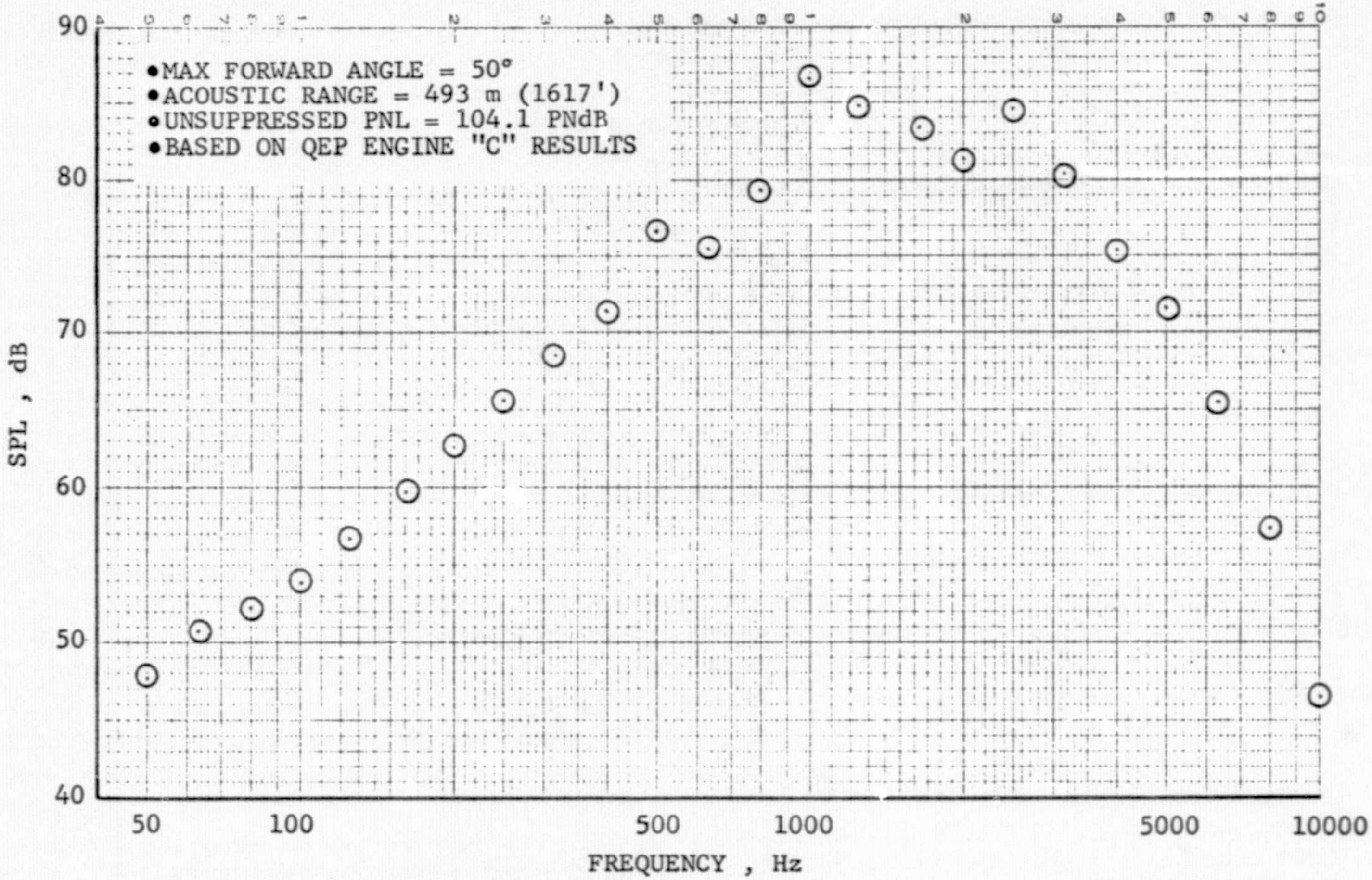


Figure 8. Estimated Full-Scale Unsuppressed Flight Spectra - Cutback.

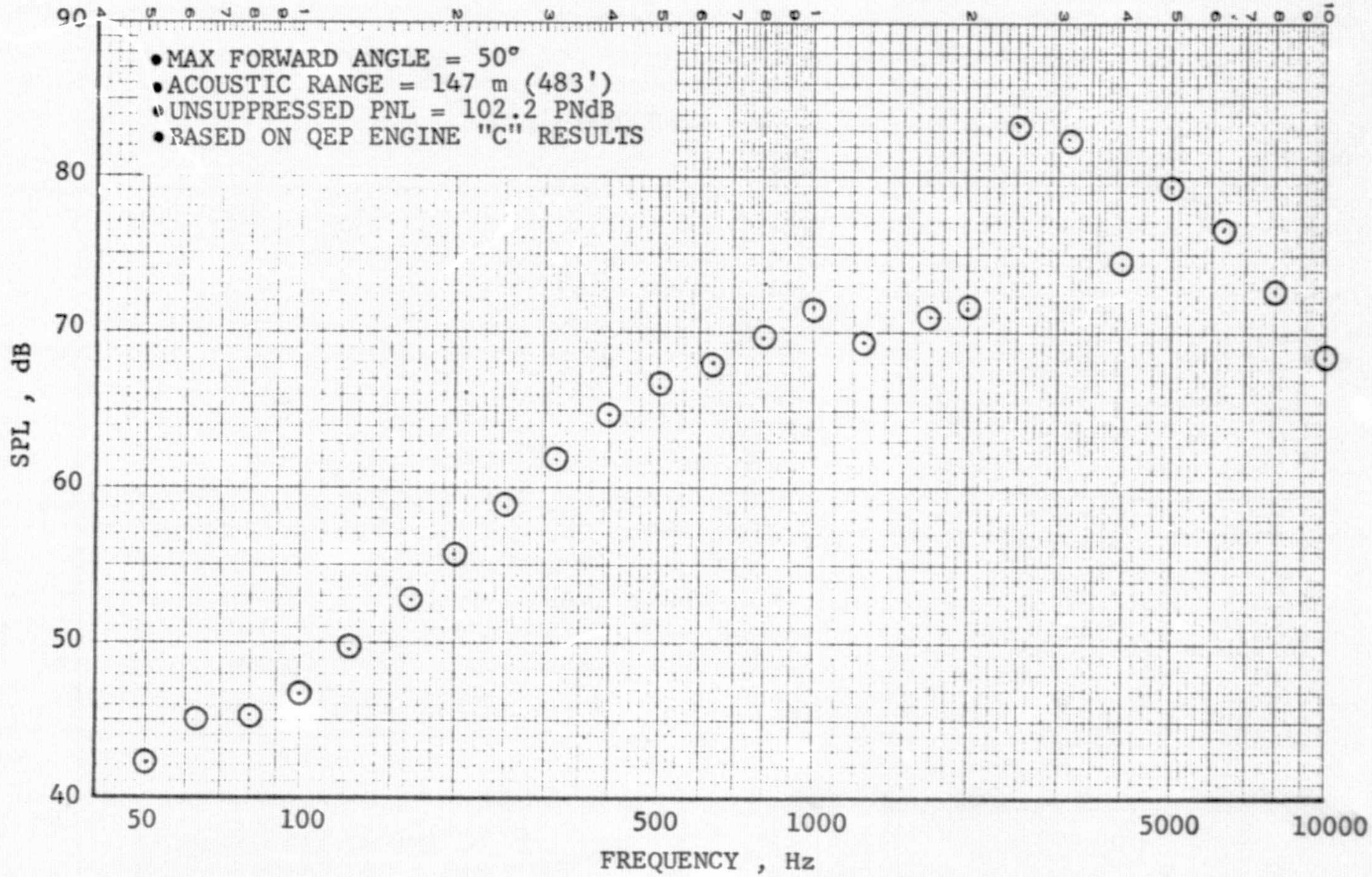


Figure 9. Estimated Full-Scale Unsuppressed Flight Spectra - Approach.

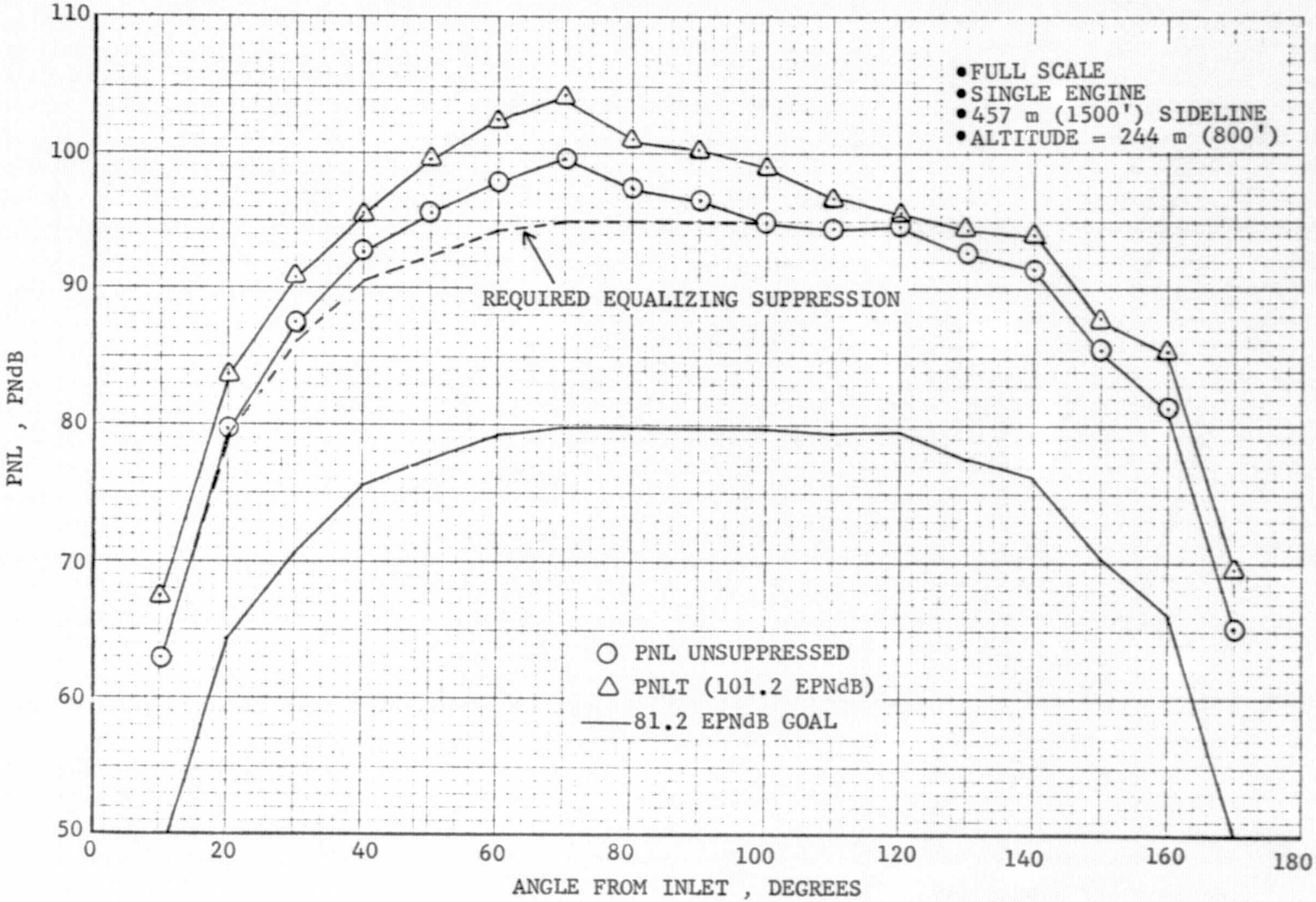


Figure 10. Comparison of Unsuppressed PNL Directivities with Goal - Takeoff.

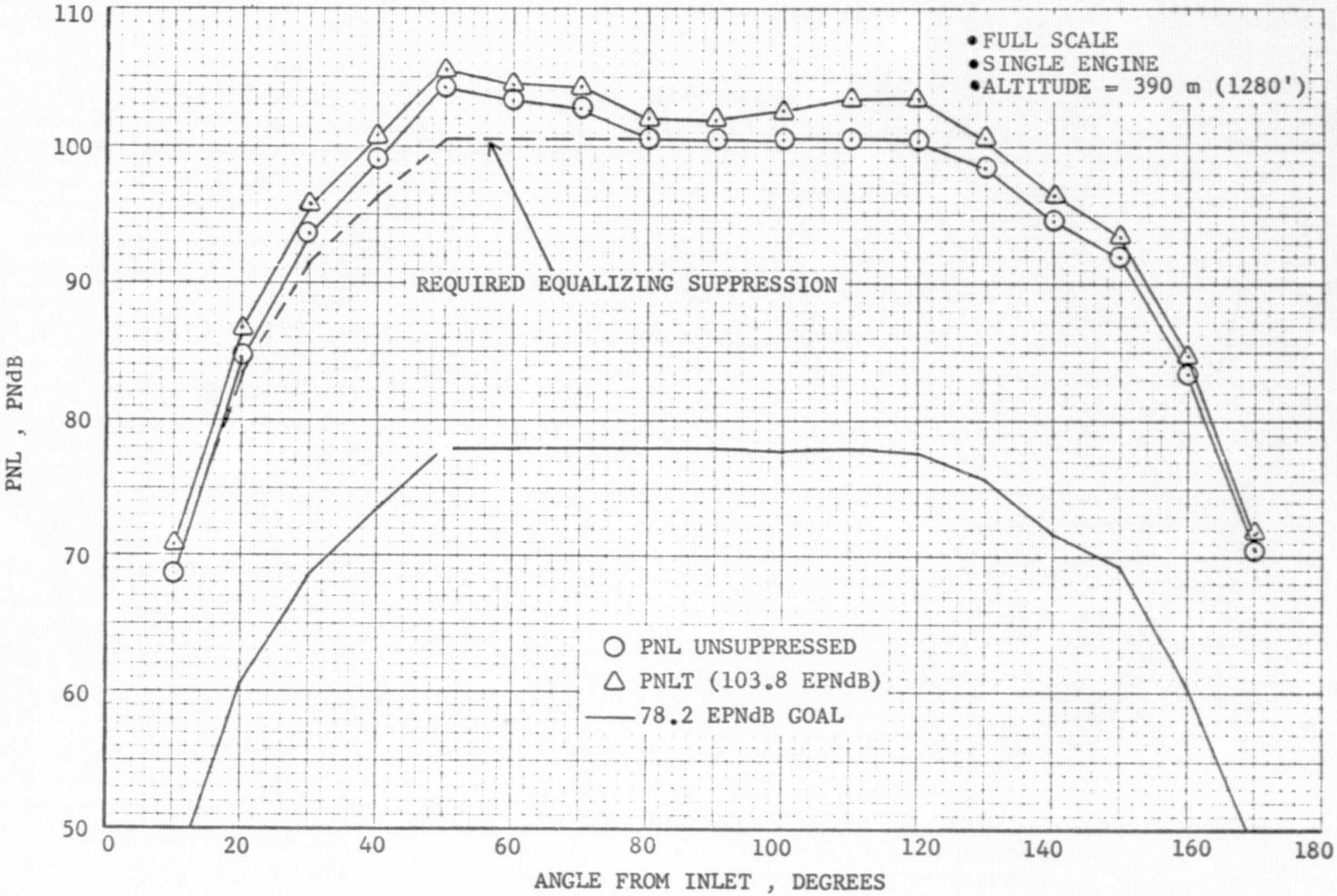


Figure 11. Comparison of Unsuppressed PNL Directivity with Goal - Cutback.

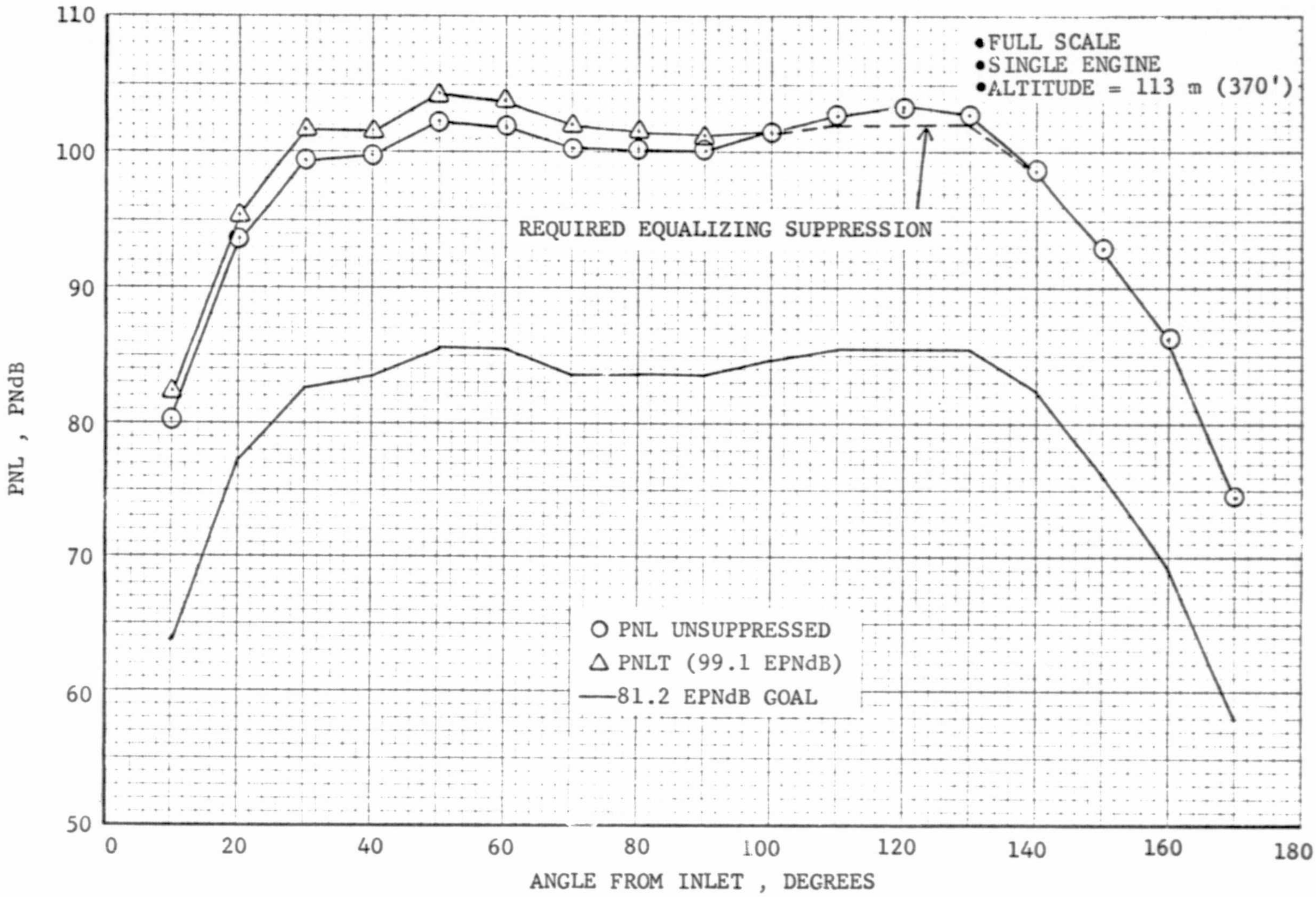


Figure 12. Comparison of Unsuppressed PNL Directivity with Goal - Approach.

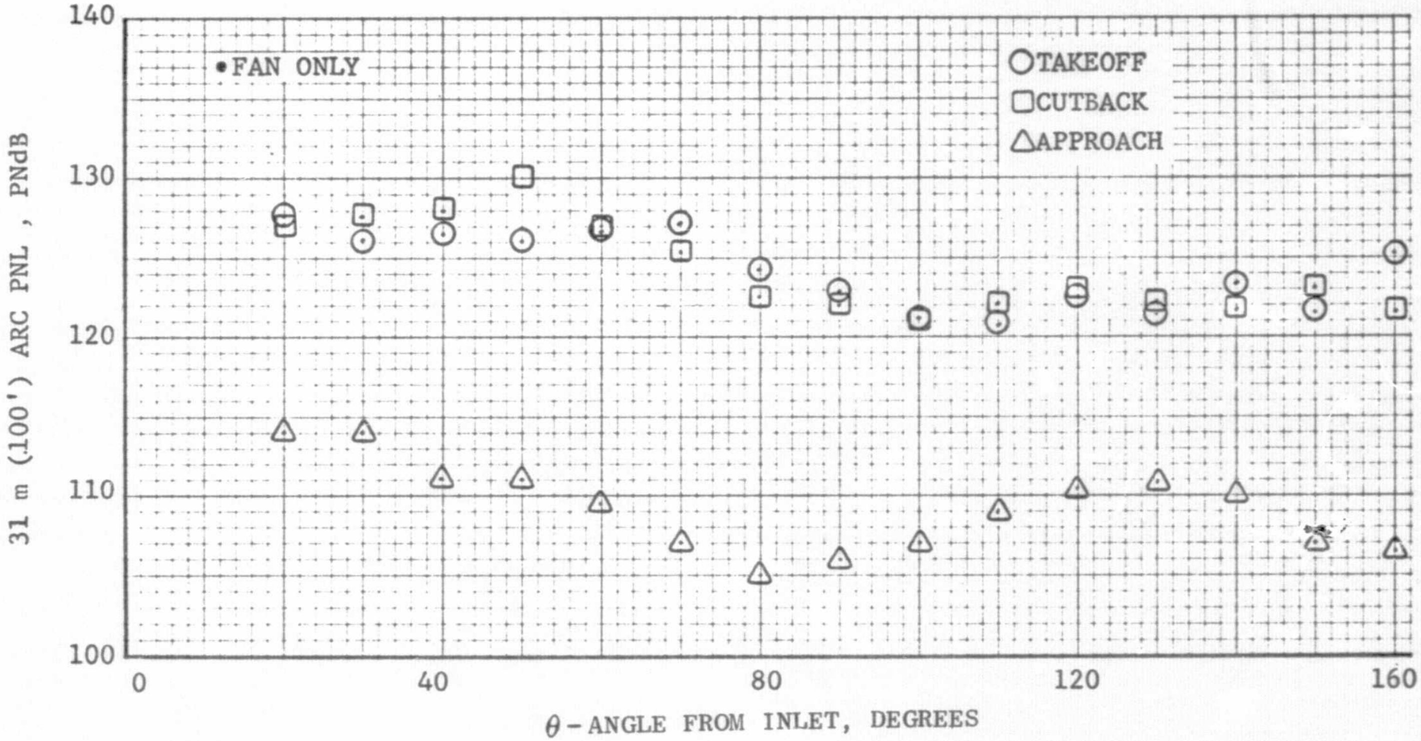
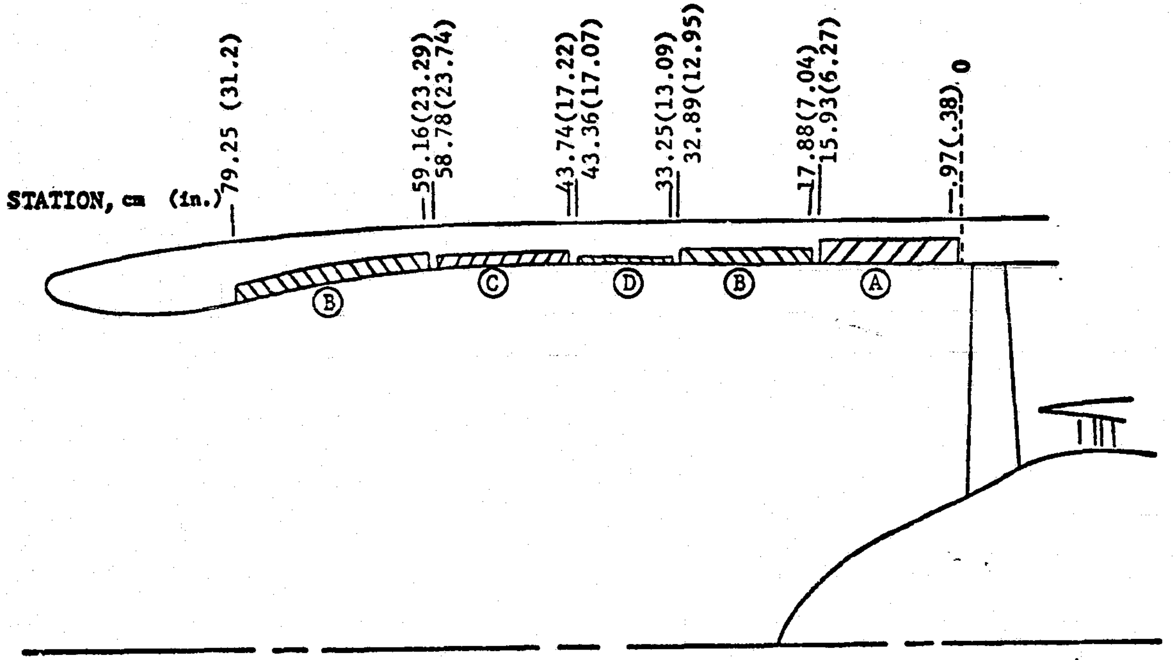


Figure 13. Scale-Model Fan Unsuppressed PNL on a 31 m (100 ft) Arc.



ACOUSTIC TREATMENT	t , cm (in)[a)]	d, cm (in)[a)]	OPEN AREA BEFORE BOND.	OPEN AREA AFTER BOND.	S , cm (in)[a)]
A	0.036(.014)	0.058(.023)	6.7$\pm$0.2%	6.0$\pm$0.2%	2.29 (.90)
B	0.036(.014)	0.058(.023)	6.7$\pm$0.2%	6.0$\pm$0.2%	0.94 (.37)
C	0.036(.014)	0.058(.023)	6.7$\pm$0.2%	6.0$\pm$0.2%	0.71 (.28)
D	0.036(.014)	0.058(.023)	6.7$\pm$0.2%	6.0$\pm$0.2%	0.36 (.14)

a) t = face plate thickness, cm (in.)
d = hole diameter, cm (in.)
S = cavity depth, cm (in.)

Figure 14. Fan Variable-Geometry Inlet Treatment Design.

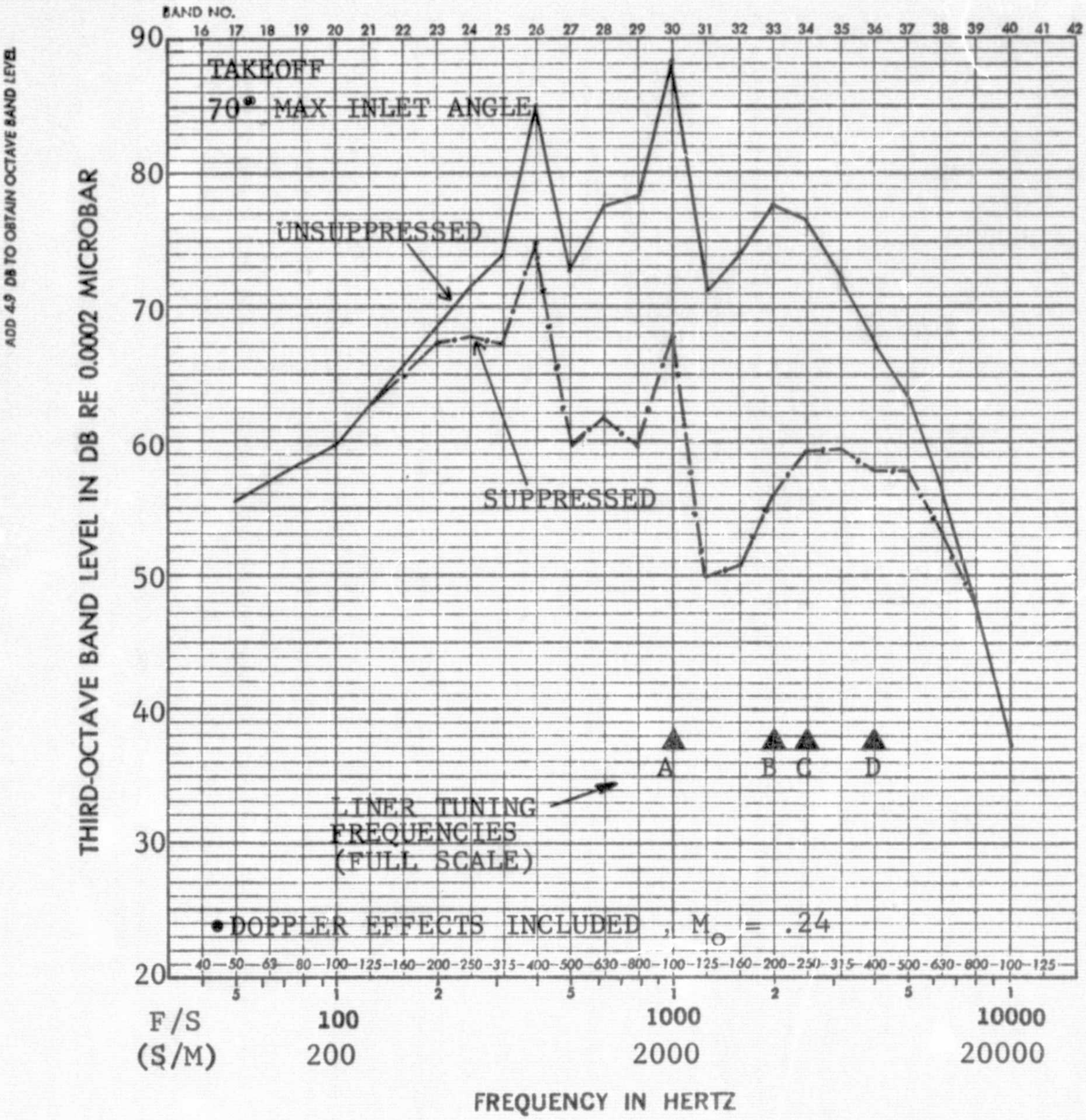


Figure 15. Takeoff SPL Spectra at 70° from the Inlet Axis.

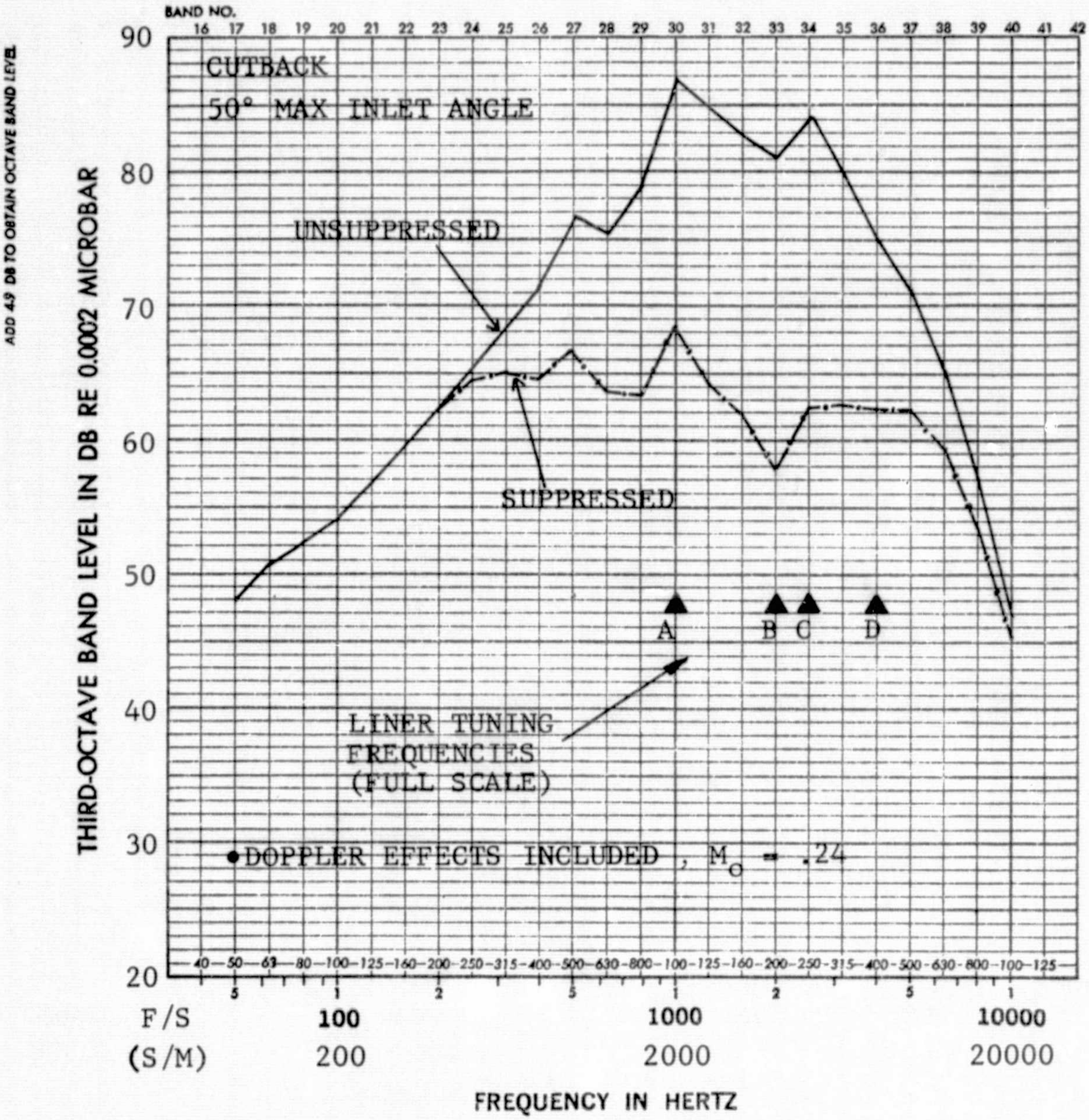


Figure 16. Cutback SPL Spectra at 50° from the Inlet Axis.

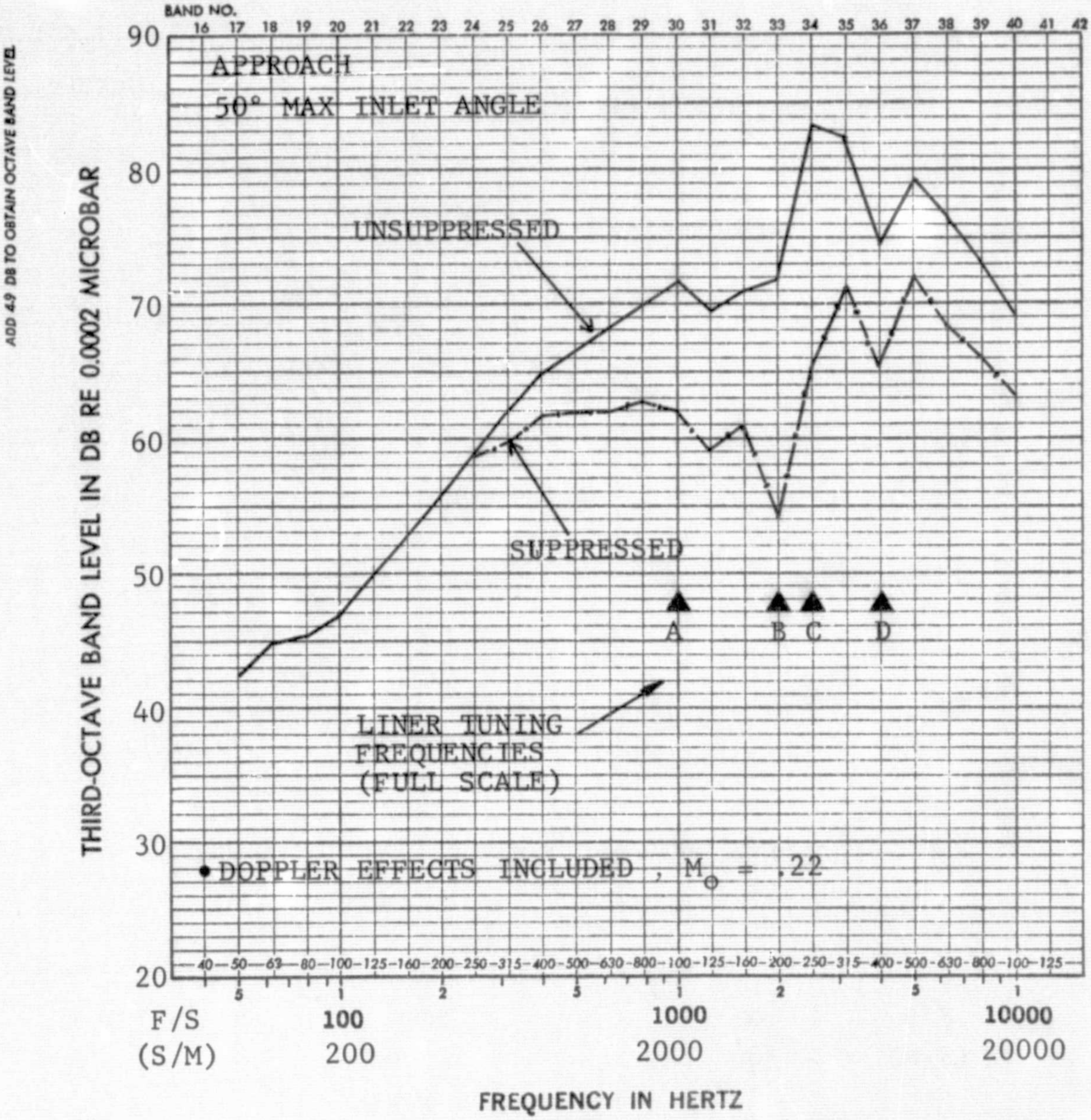


Figure 17. Approach SPL Spectra at 50° from the Inlet Axis.

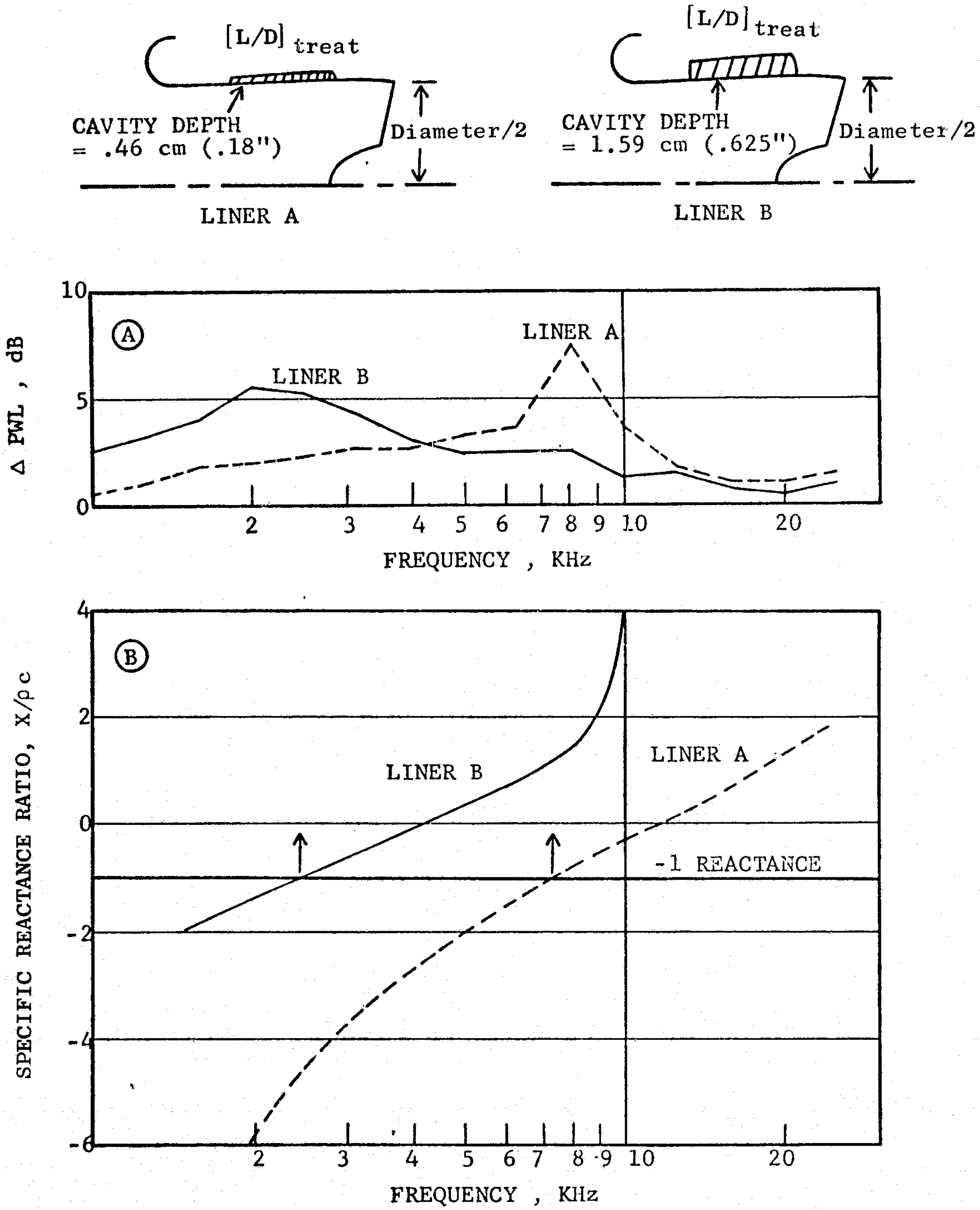


Figure 18. Example of Relationship Between Tuning Frequency and Reactance.

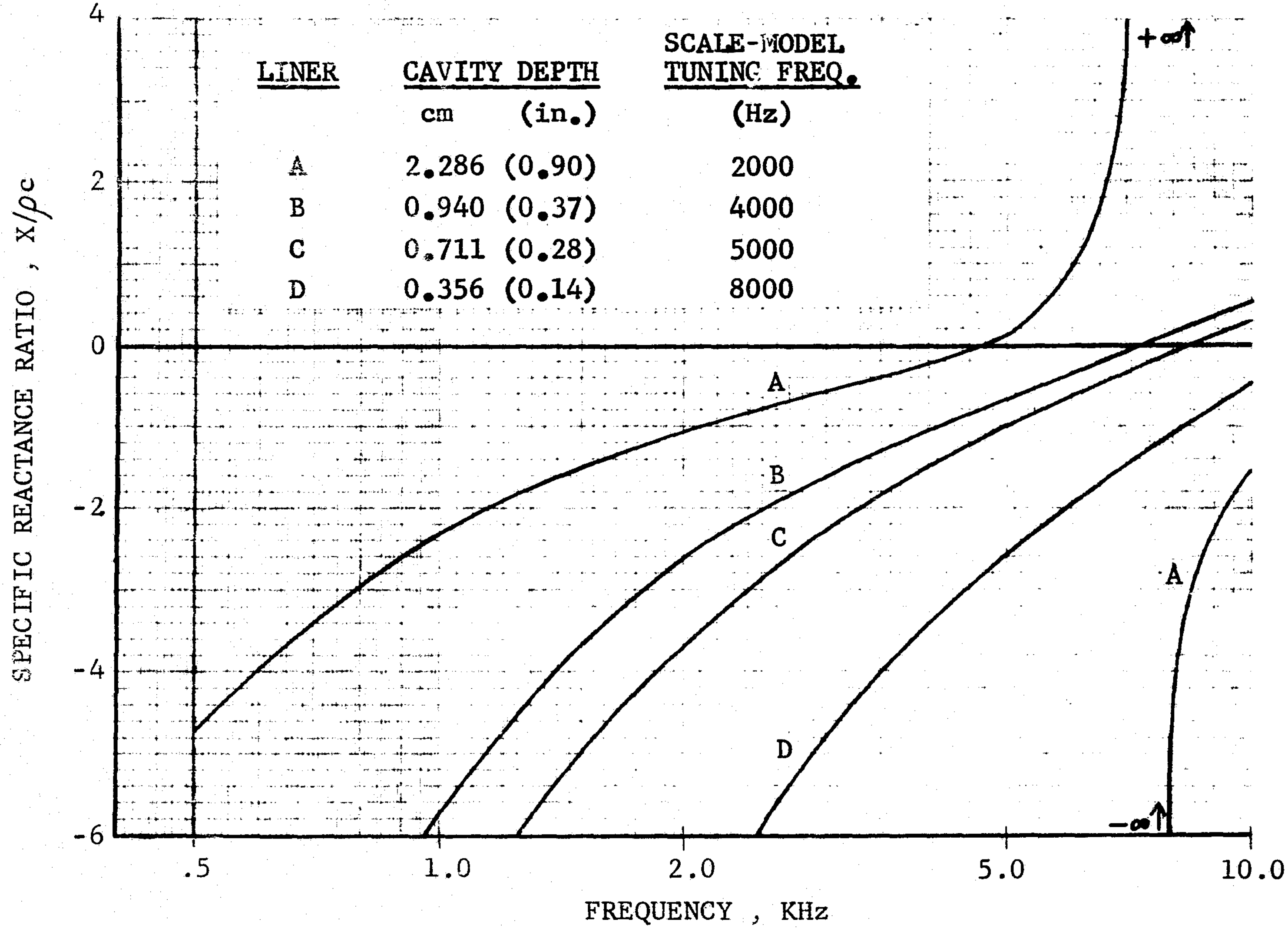


Figure 19. Specific Reactances of the Fan Inlet Duct Acoustic Treatment.

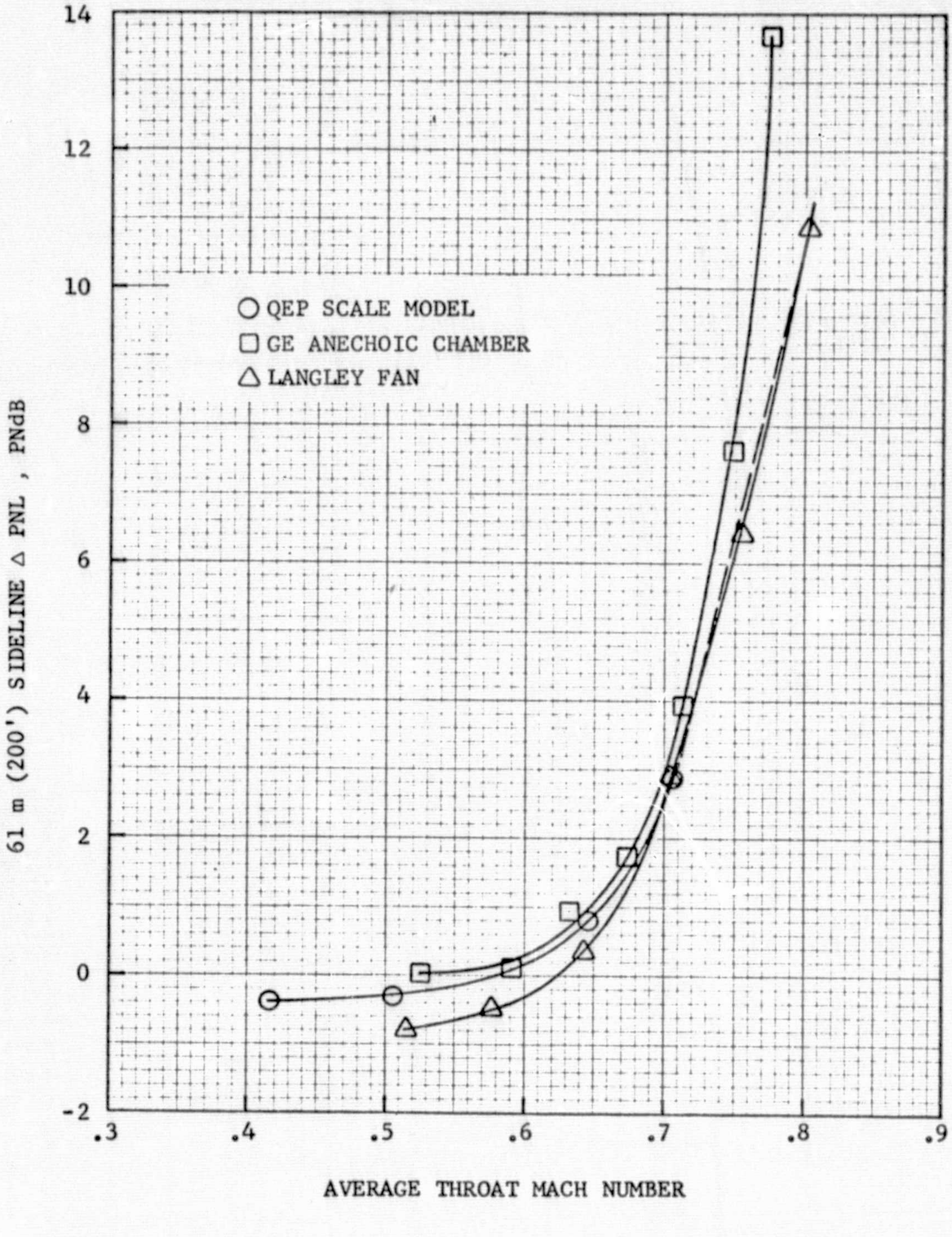
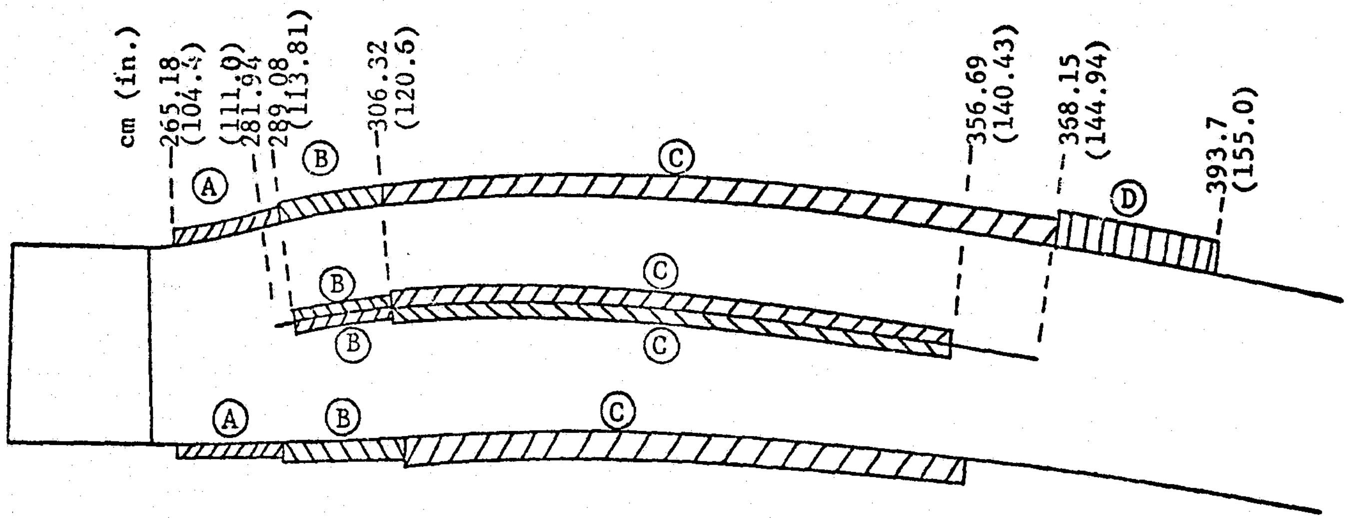


Figure 20. Inlet Acceleration Effects.



NOTE : Dimensions are Relative to Fan Blade Leading Edge at the Hub.

ACOUSTIC TREATMENT	t , cm (in)[a]	d , cm (in)[a]	OPEN AREA BEFORE BOND.	OPEN AREA AFTER BOND.	S , cm (in)[a]
A	0.046 (.018)	0.069 (.027)	17.0±2.0%	≥ 15.0%	0.24 (.09)
B	0.046 (.018)	0.069 (.027)	17.0±2.0%	≥ 15.0%	0.36 (.14)
C	0.046 (.018)	0.069 (.027)	17.0±2.0%	≥ 15.0%	0.97 (.38)
D	0.046 (.018)	0.152 (.060)	11.0±1.0%	≥ 10.0%	2.54 (1.0)

a) t = face plate thickness, cm (in.)
d = hole diameter, cm (in.)
S = cavity depth, cm (in.)

Figure 21. Fan Scale-Model Exhaust Duct, Acoustic Treatment Design.

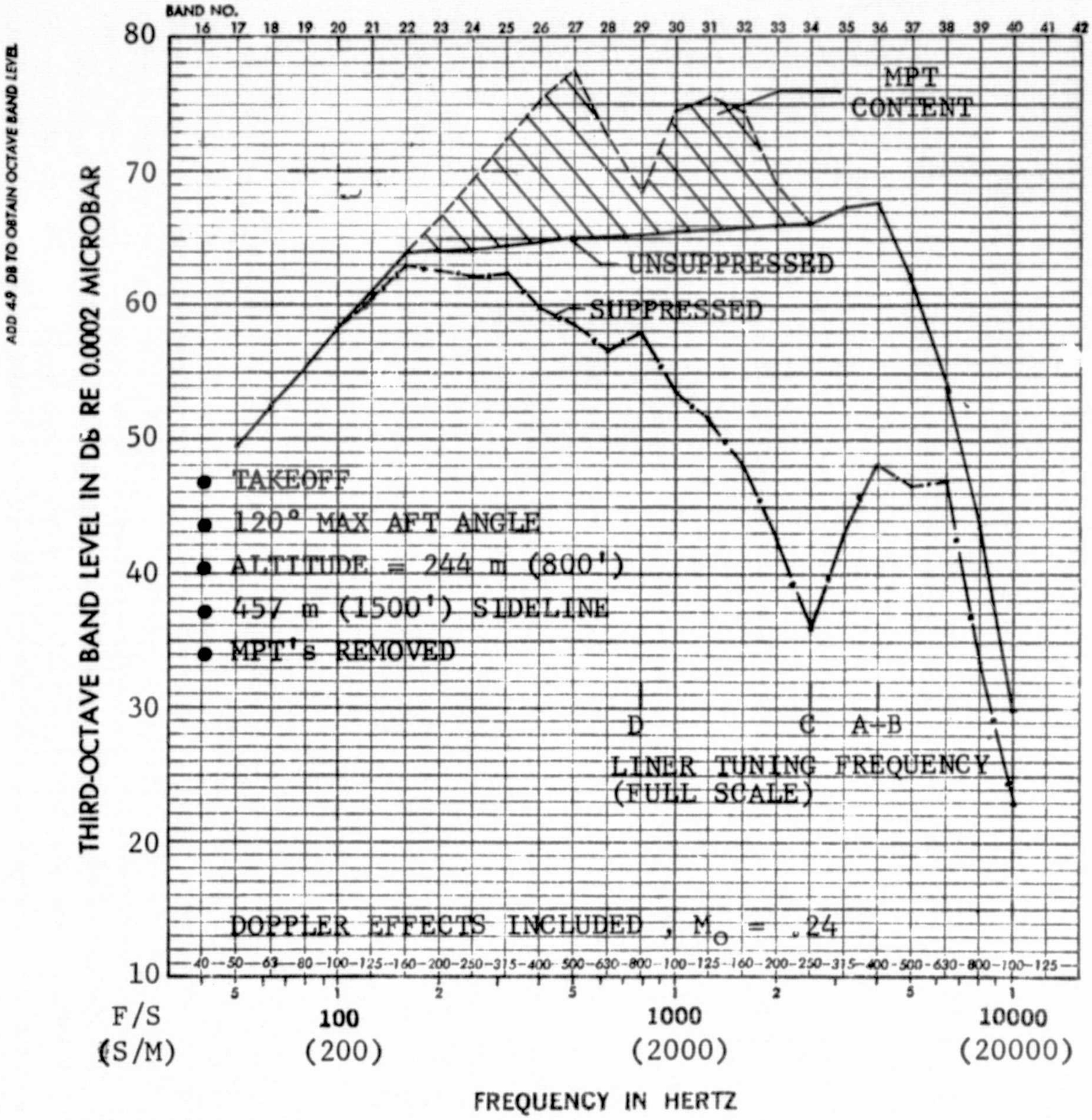


Figure 22. Takeoff Unsuppressed and Suppressed Spectra at Maximum Aft Angle.

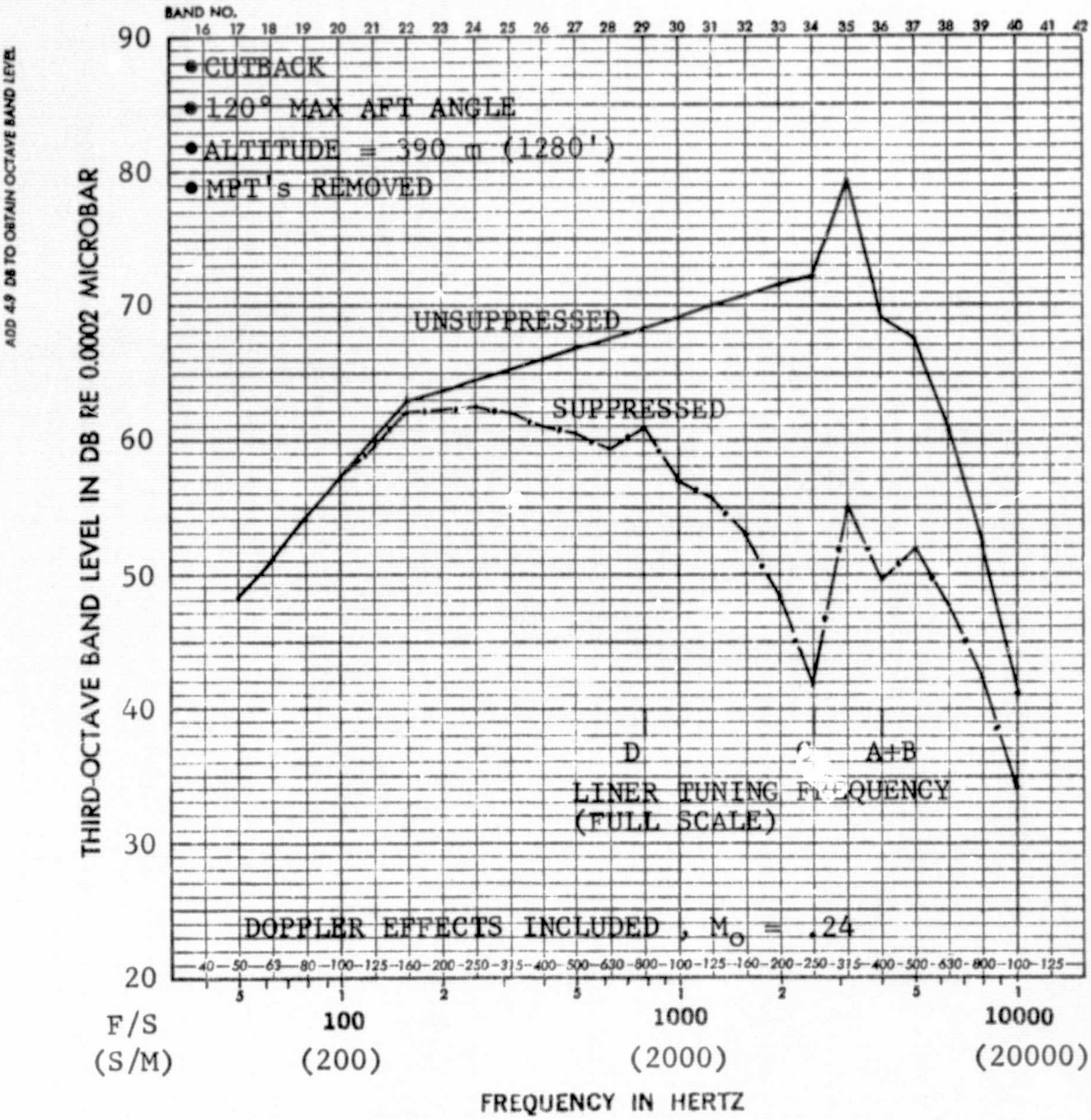


Figure 23. Cutback Unsuppressed and Suppressed Spectra at Maximum Aft Angle.

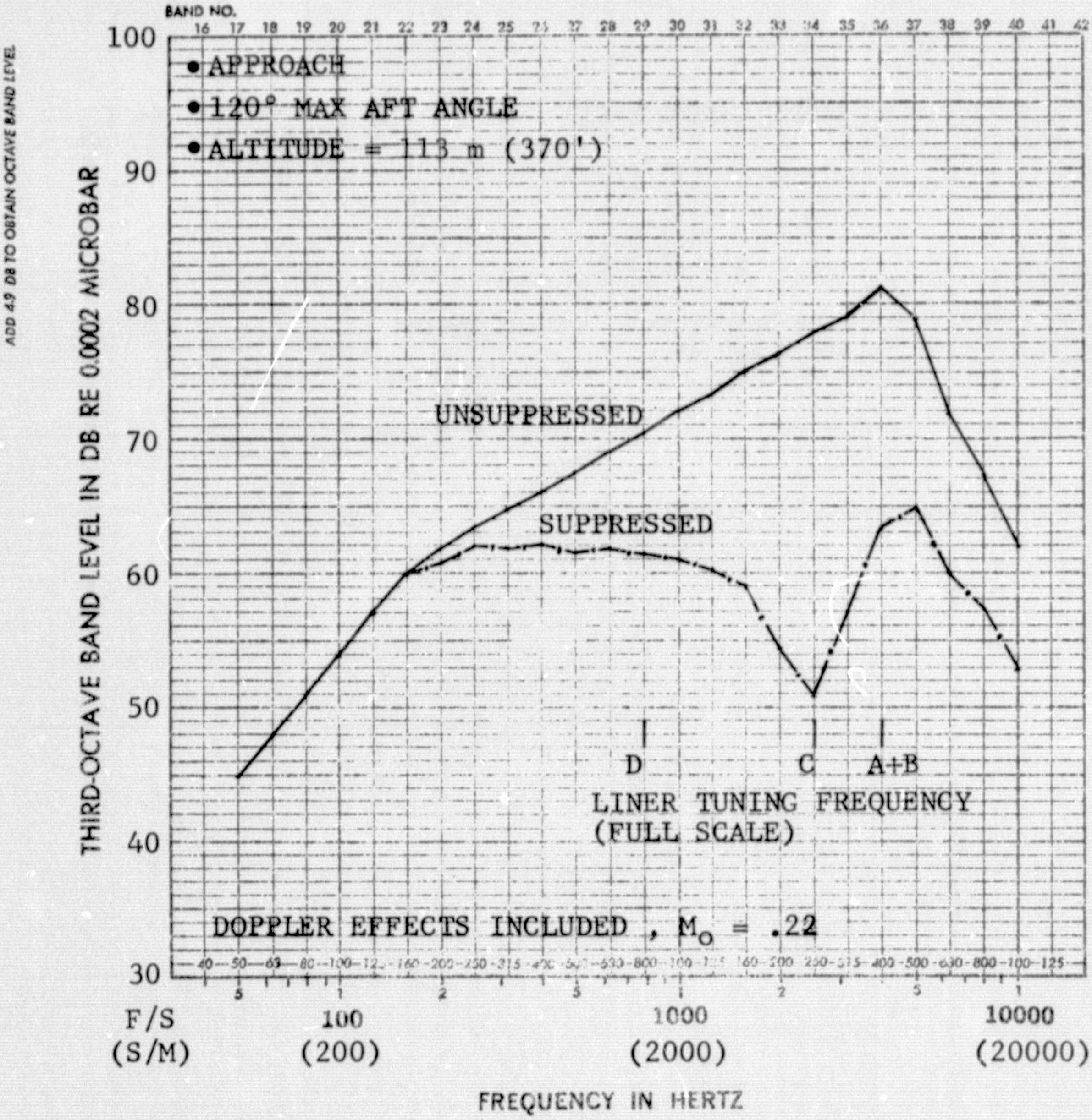


Figure 24. Approach Unsuppressed and Suppressed Spectra at Maximum Aft Angle.

LINER	PANEL DEPTH	POROSITY	HOLE DIAMETER	MACH NUMBER
	cm(in)		cm(in)	
A	.239(.094)	15%	.069(.027)	.35
B	.356(.140)	15%	.069(.027)	.34
C	.965(.380)	15%	.069(.027)	.34
D	2.54(1.000)	10%	.152(.060)	.20

FACE THICKNESS : .046cm(.018in)
SPL : 160 dB

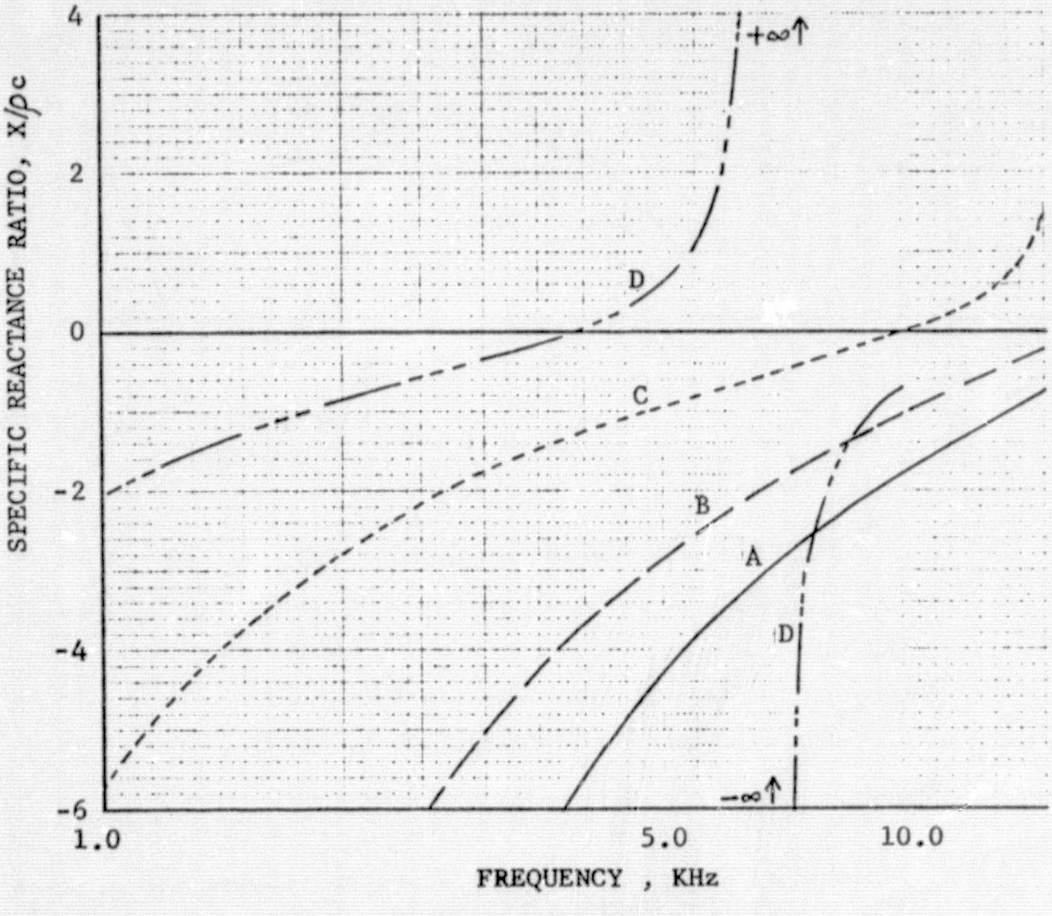


Figure 25. Specific Reactances of the Advanced Technology Fan Exhaust Duct Acoustic Treatment.

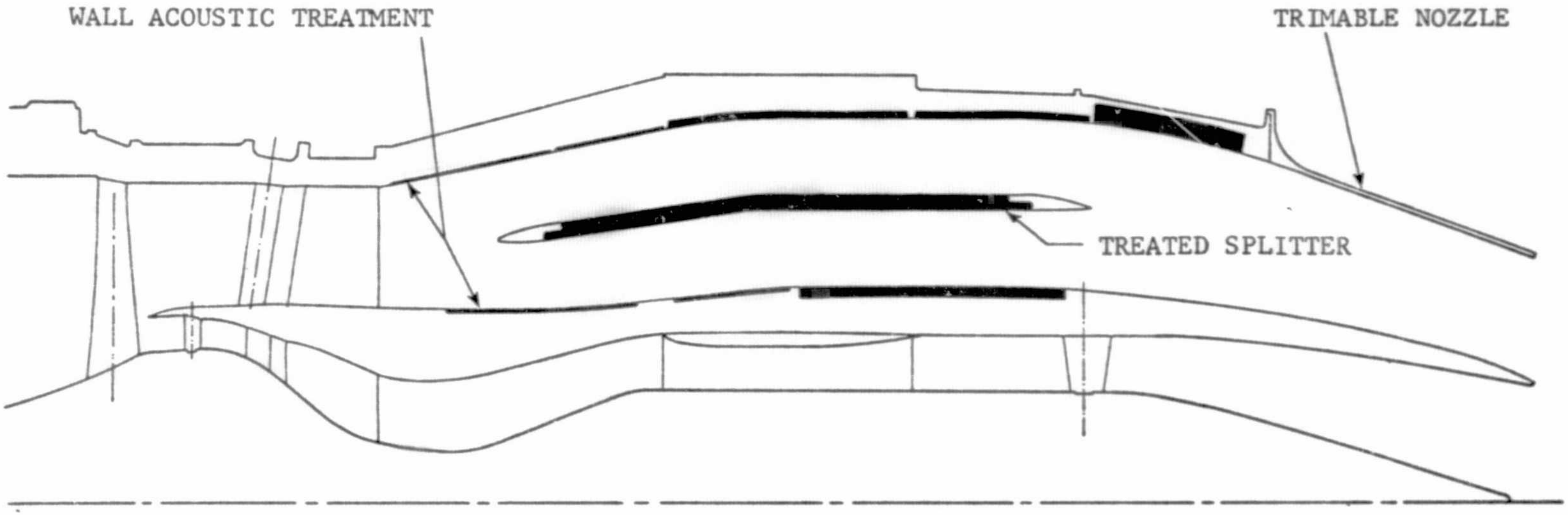


Figure 26. Advanced Technology Fan Exhaust Duct Treatment Configuration.